# TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

This Page Left Blank Intentionally

# TERRESTRIAL ENVIRONMENT (CLIMATIC) CRITERIA HANDBOOK FOR USE IN AEROSPACE VEHICLE DEVELOPMENT

## SECTION 2

## WINDS

2.1 Introduction. An aerospace vehicle's response to atmospheric disturbances, especially wind, must be carefully evaluated to ensure that its design will allow it to meet its operational requirements. The choice of criteria depends upon the specific launch location(s), vehicle configuration, and mission. The vehicle's design, operation, and flight procedures must be separated into phases for proper assessment of environmental influences and impacts upon its life history. These phases include (1) the initial purpose and concept of the vehicle, (2) its preliminary engineering design for flight, (3) its structural design, (4) its guidance and flight control design, (5) optimizations of its design limits, and (6) the final assessment of its capability for launch and operations.

Because the wind environment significantly affects the design and operation of aerospace vehicles, and it is necessary to use good technical judgment and to apply sound engineering principles in preparing wind criteria that are descriptive and representative. Although wind criteria guidelines contained in this document were especially prepared for application to aerospace vehicle programs, they are applicable to other areas such as aeronautical engineering, architecture, atmospheric diffusion, wind and solar energy conversion research, and many others. The proper selection, analysis, and interpretation of wind information are responsibilities of the atmospheric scientists working in collaboration with the design engineers.

The information given in this document covers wind models and criteria guidelines applicable to various design problems. The risk level selected for the design depends upon the design philosophy used by management for the aerospace vehicle development effort. To maximize vehicle performance flexibility, it is considered best to utilize those wind data associated with the minimum acceptable risk levels. In addition, the critical mission-related parameters, such as exposure time of the vehicle being affected by the natural environment quantities, launch windows, reentry periods, launch turnaround periods, etc., should be considered carefully. Initial design work using unbiased (with respect to wind) trajectories based on non-directional ground or in-flight winds may be used unless the vehicle and its mission are well known and the exact launch azimuth and time(s) are established and adhered to throughout the program. In designs that use wind-biased trajectories and directional (vector) wind criteria, rather severe wind constraints can result if the vehicle is used for other missions, different flight azimuths, or if other vehicle configurations are developed. Therefore, caution must be exercised in using wind criteria models to ensure consistency with the physical interpretation of each specific vehicle design problem relative to the overall design philosophy for the vehicle. Several references are cited throughout this document which discuss special and specific problems related to the development and specification of wind environments for aerospace vehicle programs.

A comprehensive review of wind models and studies that have been derived and used on various NASA Aerospace Vehicles, including the Space Shuttle is documented in NASA-CR-1998-208859, *"A Compendium of Wind Statistics and Models for the NASA Space Shuttle and other Aerospace Vehicle Programs".*

## 2.2 Ground Wind (1 to 150 m)

2.2.1 Introduction. Ground winds for aerospace vehicle development applications are defined in this document to be those winds in the lowest 150 m of the atmosphere. The winds in this layer of the atmosphere are characterized by very complicated three-dimensional flow patterns with rapid variations in magnitude and direction in space and time. An engineering requirement exists for models which define the structure of wind in this layer because of the complicated and possibly critical manner in which a vehicle might respond to certain aspects of the flow, both when the vehicle is stationary on the launch pad and during the first few seconds after the launch. The forces generated by von Karman vortex shedding are an example of the effect of wind on aerospace vehicles. These forces can result in base bending moments while the vehicle is on the launch pad and pitch and yaw plane angular accelerations and vehicle drift during lift-off. Other equally important examples can be cited. The basic treatment of the ground wind problem relative to vertically oriented vehicles on-pad and during lift-off has been to estimate the risk of encountering crucial aspects of wind along the vertical. It should be noted that, in addition to the engineering requirements for on-pad and launch winds for vertically ascending vehicles, a requirement for ground wind models also exists for horizontally flying vehicles for take-off and landing. This aspect of the natural wind environment is discussed in sections 2.3.13 through 2.3.16.

Because ground wind data are applied by aerospace vehicle engineers in numerous ways, dependent upon the specific problem, various viewpoints and kinds of analytical techniques were used to obtain the environmental models presented here. Program planning, for instance, requires considerable climatological insight to determine the frequency and persistence distributions for wind speeds and wind directions. However, for design purposes, the aerospace vehicle must withstand certain unique predetermined structural loads that are generated from exposure to known peak ground wind conditions. Ground wind profiles and the ground wind turbulence spectra contribute to the development of the design ground wind models. Surface roughness, launch site structures, thermal environment, and various transient local and large-scale meteorological systems influence the ground wind environment for each launch site.

2.2.2 Considerations in Ground Wind Design Criteria. To establish the ground wind design criteria for aerospace vehicles, several important factors must be considered.

a. Where is the vehicle to operate?
b. What is the launch location?
c. What are the proposed vehicle missions?
d. How many hours, days, or months will the vehicle be exposed to ground winds?
e. What are the consequences of operational constraints that may be imposed upon the vehicle because of wind constraints?
f. What are the consequences if the vehicle is destroyed or damaged by ground winds?
g. What are the cost and engineering practicalities for designing a functional vehicle to meet the desired mission requirements?
h. What is the risk that the vehicle will be destroyed or damaged by excessive wind loading?

In view of this list of questions or any similar list that a design group may enumerate, it becomes obvious that the establishment of ground wind environment design criteria for a aerospace vehicle requires an interdisciplinary approach involving several engineering and scientific disciplines. Furthermore, the process is an iterative one. To begin the iterative process, specific information on ground winds is required.

2.2.3 Introduction to Exposure Periods Analysis. Valid, quantitative answers to such questions as the following are of primary concern in the design, mission planning, and operation of aerospace vehicles:

a. What is the probability that the peak ground wind at some specified reference height will exceed (or not exceed) a given magnitude in some specified time period?

b. Given a design wind profile in terms of peak wind speed versus height from 10 to 150 m, what is the probability that the design wind profile will be exceeded in some specified time period?

Given a statistical sample of peak wind measurements for a specific location, the first question can be answered in as much detail as a statistical analyst finds necessary and sufficient. This first question has been thoroughly analyzed for Kennedy Space Center (KSC), partially for Vandenberg Air Force Base (VAFB), and to a lesser degree for other locations of interest.

The analysis becomes considerably more complex in answering the second question. A wind profile is required, and, to develop the model, measurements of the wind profiles by properly instrumented ground wind towers are required as well as a program for scheduling the measurements and data reduction. Every instantaneous wind profile is unique; similarity is a matter of degree. Given the peak wind speed at one height, there is a whole family of possible profiles extending from the specified wind at that height. Thus for each specified wind speed at a given height, there is a statistical distribution of wind profiles. Recommended profile shapes for KSC and other locations are given in this document. The analysis needed to answer the second question is not complete, but we can assume that, given a period of time, the design wind profile shape will occur for a specified wind speed at a given height. For example, in the event that a thunderstorm passes over the vehicle, it is logical to assume that the design wind profile shape will occur and that the chance of the design wind profile being exceeded is the same as the probability that the peak wind (gust) during the passage of the thunderstorm will strike the vehicle or point of interest (Ref. 2-1).

2.2.4 Development of Extreme Value Concept. It has been estimated from wind tunnel tests that only a few seconds are required for the wind to produce near steady-state drag loads on a vehicle such as the space shuttle in an exposed condition on the launch pad. For this and other reasons, we have adopted the peak wind speed as our fundamental measurement of wind for use in design studies. Equally important, when the engineering applications of winds can be made in terms of peak wind speeds, it is possible to obtain an appropriate statistical sample that conforms to the fundamental principles of extreme value theory. One hour is a convenient and physically meaningful minimum time interval from which to select the peak wind. An hourly peak wind speed sample has been established for KSC from wind information on continuous recording charts. Representative peak wind samples for VAFB have been derived from hourly steady-state wind measurements using statistical and physical principles. From the hourly peak wind records, the daily peak, and monthly peak wind records can be computed. An extreme value probability function is used to summarize these statistics.

2.2.4.1 Envelope of Distributions. In the development of the statistics for peak winds, it was recognized that the probability of hourly, daily, and monthly peak winds exceeding (or not exceeding) specified values varied with time of day and from month to month. The Gumbel extreme value probability distribution (Ref. 2.56) was an excellent fit to the samples of hourly, daily, monthly, bimonthly (in two combinations), and trimonthly (in three combinations) periods taken over the complete period of record, thereby justifying the use of this distribution. However, in establishing vehicle wind design criteria for the peak winds versus exposure time, it is desired to present a simple set of wind statistics in such a manner that every reference period and exposure time would not have to be examined to determine the probability that the largest peak wind during the exposure time would exceed some specified magnitude. To accomplish this objective, envelopes of the distributions of the largest peak winds for various time increments for the various reference periods were constructed. For example, to obtain the envelope distribution of hourly peak winds for the month of March, the largest peak wind was selected at each percentage point from the 24 peak wind distributions (one for each hour). For a 365-day exposure, the distribution for the extreme largest yearly peak wind data sample is used.

Selected wind profile envelopes of distributions are given in subsection 2.2.5.5. It is recommended that these envelopes of distributions be used for vehicle wind design considerations. This recommendation is made under the assumption that it is not known what time of day or season of year critical vehicle operations are to be conducted. Furthermore, it is not desirable to design a vehicle to operate only during selected hours or months. Should all other design alternatives fail to lead to a functionally engineered vehicle with an acceptable risk of not being compromised by wind loads, then distributions for peak winds by time of day for monthly reference periods may be considered for limited missions. For vehicle operations, detailed statistics of peak winds for specific missions are meaningful for management decisions, in planning missions, and in establishing mission rules and alternatives for the operational procedures. To present the wind statistics for these purposes is beyond the scope of this document. Each space mission has many facets that make it difficult to generalize and to present all the available statistics in brief form.

2.2.5 Design Wind Profiles for Aerospace Vehicles. Specific information about the wind profile is required to calculate ground wind loads on aerospace vehicles. The Earth's surface is a rigid boundary that exerts a frictional force on the lower layers of the atmosphere, causing the wind to approach zero velocity at the ground. In addition, the characteristic length and velocity scales of the mean (steady-state) flow in the first 150 m (boundary layer) of the atmosphere combine to yield extremely high Reynolds numbers with values that range between approximately $10^6$ and $10^8$, so that for most conditions (wind speeds >1 m/s) the flow is fully turbulent. The lower boundary condition, the thermal and dynamic stability properties of the boundary layer, the distributions of the large-scale pressure, the Coriolis force, and the structure of the turbulence combine to yield an infinite number of wind profiles.

Data on basic wind speed profiles given in this section are for use in vehicle design studies. With respect to design practices, the application of peak winds and the associated turbulence spectra and discrete gusts should be considered. The maximum response obtained for the selected risk levels for each physically realistic combination of conditions should be employed in the design. Care should be exercised so that wind inputs are not taken into account more than once. For example, the discrete gust and spectrum (a discrete bandwidth of energy in the turbulent spectrum) of turbulence are representations of the same thing, namely atmospheric turbulence. Thus, one should not calculate the responses of a vehicle due to the discrete gust and spectrum and then combine the results by addition, root-sum-square, or any other procedure since these inputs represent the same thing. Rather, the responses should be calculated with each input and then enveloped.

2.2.5.1 Philosophy. An example of a peak wind speed is given in figure 2-1. Peak wind statistics have three advantages over mean wind statistics. First, peak wind statistics do not depend upon an averaging operation as do mean wind statistics. Second, to construct a mean wind sample, a chart reader or weather observer must perform an "eyeball" average of the wind data, causing the averaging process to vary from day to day according to the mood of the observer, and from observer to observer. Hourly peak wind speed readings avoid this subjective averaging process. Third, to monitor winds during the countdown phase of an aerospace vehicle launch, it is easier to monitor peak wind speed than the mean wind speed. With today's modern electronic computational techniques available, monitoring a mean wind speed over any given time interval is not as serious a problem.

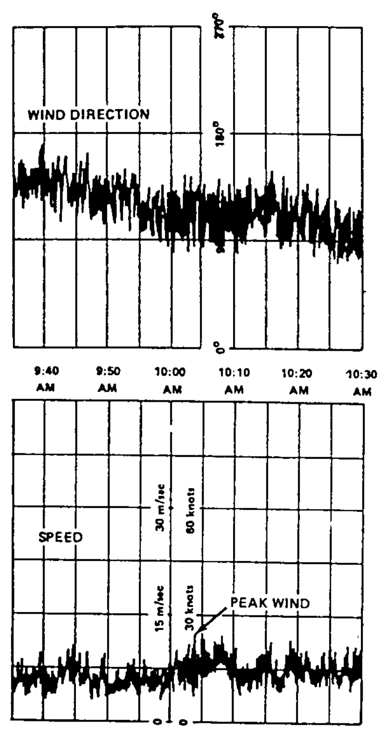



FIGURE 2-1. Example of Peak Wind Speed and Direction Records.

Smith et al. (Ref. 2-2) have performed extensive statistical analyses with peak wind speed samples measured at the 10-m level. In the course of the work, he and his collaborators introduced the concept of exposure period probabilities into the design and operation of aerospace vehicles. By determining the distribution functions of peak wind speeds for various periods of exposure (hour, day, month, year, etc.), it is possible to determine the probability of a certain peak wind speed magnitude occurring during a prescribed period of exposure. Thus, if an operation requires, for example, 1 hour to complete, and if the critical wind loads on the aerospace vehicle can be defined in terms of the peak wind speed, then it is the probability of occurrence of the peak wind speed during a 1-hour period that gives a measure of the risk of the occurrence of structural failure. Similarly, if an operation requires 1 day to complete, then it is the probability of occurrence of the peak wind speed during a 1-day period that gives a measure of the risk of structural failure.

These peak wind statistics are usually transformed to the 18.3-m (60-ft) reference level for design purposes (or sometimes to higher levels for operational applications). However, to perform loading and response calculations resulting from steady-state and random turbulence drag loads and von Karman vortex shedding loads, the engineer requires information about the vertical variation of the mean wind and the structure and turbulence in the atmospheric boundary layer. The philosophy is to extrapolate the peak wind statistics up in height via a peak wind profile, and the associated steady-state or mean wind profile is obtained by applying a gust factor that is a function of wind speed and height.

2.2.5.2 Peak Wind Profile Shapes. To develop a peak wind profile model, approximately 6,000 hourly peak wind speed profiles measured at NASA's ground wind tower facility at KSC have been analyzed. The sample, composed of profiles of hourly peak wind speeds measured at the 18-, 30-, 60-, 90-, 120-, and 150-m levels, showed that the variation of the peak wind speed in the vertical, below 150 m, for engineering purposes, could be described with a power law relationship given by

$$u(z) = u_{18.3}\left(\frac{z}{18.3}\right)^{k} , \qquad (2.1)$$

where $u(z)$ is the peak wind speed at height $z$ in meters above the natural grade and $u_{18.3}$ is a known peak wind speed at $z$ = 18.3 m. The peak wind is referenced to the 18.3-m level because this level has been selected as the standard reference for the KSC launch area. A reference level should always be stated when discussing ground winds to avoid confusion in interpretation of risk statements and structural load calculations.

A statistical analysis of the peak wind speed profile data revealed that, for engineering purposes, $k$ is distributed normally for any particular value of the peak wind speed at the 18.3-m level. Thus, for a given percentile level of occurrence, $k$ is approximately equal to a constant for $u_{18.3} \leq 2$ m/s. For $u_{18.3} > 2$ m/s,

$$k = c(u_{18.3})^{-3/4} , \qquad (2.2)$$

where $u_{18.3}$ has the units of meters per second. The parameter $c$, for engineering purposes, is distributed normally with mean value 0.52 and standard deviation 0.36 and has units of $(\text{m/s})^{3/4}$. The distribution of $k$ as a function of $u_{18.3}$ is depicted in figure 2-2. The $\bar{k} + 3\,\sigma$ values are used in design studies.

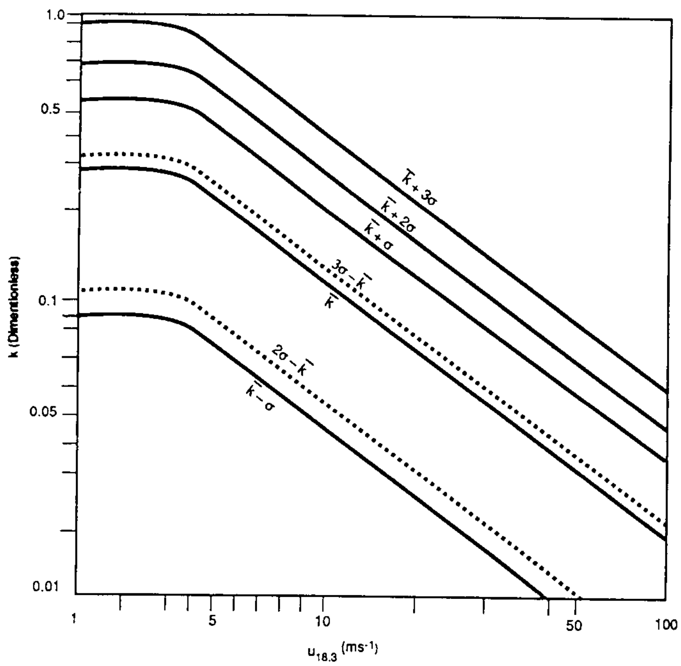



FIGURE 2-2. Distribution of the Peak Wind Profile Parameter k for Various Peak Wind Speeds at the 18.3-m Level for KSC.

2.2.5.3 Instantaneous Extreme Wind Profiles. The probability that the hourly peak wind speeds will occur at all levels simultaneously is small. Accordingly, the practice of using peak wind profiles introduces some conservatism into the design criteria; however, the probability is relatively large that when the hourly peak wind occurs at the 18.3-m level, the winds at the other levels almost take on the hourly peak values.

To gain some insight into this question, approximately 35 hours of digitized magnetic tape data were analyzed. The data were digitized at 0.2-s intervals in real time and partitioned into 0.5-, 2-, 5-, and 10-min samples. The vertical average peak wind speed $u_P$ and the 18-m mean wind $\bar{u}_{18}$ were calculated for each sample. In addition, the instantaneous vertical average wind speed time history at 0.2-s intervals was calculated for each sample, and the peak instantaneous vertical average wind speed $u_I$ was selected for each sample. The quantity $\bar{u}_I / \bar{u}_P$ was then interpreted to be a measure of how well the peak wind profile approximated the instantaneous extreme wind profile.

Figure 2-2A is a plot of $\bar{u}_I / \bar{u}_P$ as a function of $\bar{u}_{18}$. The data points tend to scatter about a mean value of $\bar{u}_I / \bar{u}_P$ 0.93; however, some of the data points have values equal to 0.98. These results justify the use of peak wind profiles for engineering design purposes.

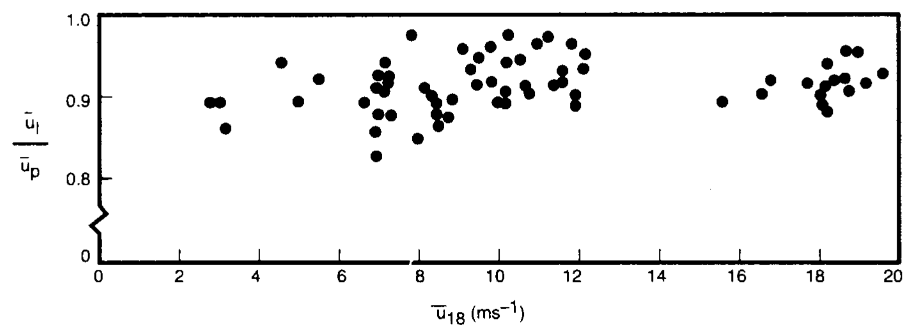



FIGURE 2-2A. The Ratio $\bar{u}_I$ / $\bar{u}_P$ as a Function of the 18.3-M Level Mean Wind Speed ($\bar{u}_{18}$) for a 10-Min Sampling Period.

2.2.5.4 Peak Wind Profile Shapes for Other Test Ranges and Sites. Detailed analyses of wind profile statistics are not available for test ranges and sites other than KSC. The exponent *k* in equation (2.1) is a function of wind speed, surface roughness, etc. For moderate surface roughness conditions, the extreme value of *k* is usually equal to 0.2 or less during high winds (≈ >15 m/s). For design and planning purposes for test ranges and sites other than KSC, it is recommended that the values of *k* given in Table 2-1 be used. These values of *k* are the only values specified in this document for sites other than KSC and represent estimates for 99.87 percentile, or +3σ (0.13-percent risk), values for the peak wind speed profile shape. A recent study resulted in *k* = 0.085 for EAFB, with associated peak wind speeds corresponding to an altitude of 4 m (13 ft).

TABLE 2-1. Values of k to Use for Test Ranges Other than KSC.

| *k* Value | 18.3-m Level Peak Wind Speed (m/s) |
|---|---|
| *k* = 0.2 | $7 \leq u_{18.3} < 22$ |
| *k* = 0.14 | $22 \leq u_{18.3}$ |

2.2.5.5 Aerospace Vehicle Design Wind Profiles. The data presented in this section provide basic peak wind speed profile (envelope) information for test, free-standing, launch, and lift-off conditions to ensure satisfactory performance of an aerospace vehicle. To establish vehicle responses, the peak design surface winds are assumed to act normal to the longitudinal axis of the vehicle on the launch pad and to be from the most critical direction.

2.2.5.5.1 Design Wind Profiles for Kennedy Space Center. Peak wind profiles are characterized by two parameters, the peak wind speed at the 18.3-m level and the shape parameter *k*. Once these two quantities are defined, the peak wind speed profile envelope is completely specified. Accordingly, to construct a peak wind profile for KSC, in the context of launch vehicle loading and response calculations, two pieces of information are required. First, the risk of exceeding the design wind peak speed at the reference level for a given period must be specified. Once this quantity is given, the design peak wind speed at the reference level is automatically specified (Fig. 2-3). Second, the risk associated with compromising the structural integrity of the vehicle, once the reference level design wind occurs, must be specified. This second quantity and the reference level peak wind speed will determine the value of *k* that is to be used in equation (2.1).

It is recommended that the $\bar{k}+3\sigma$ value of $k$ be used for the design of aerospace vehicles. Thus, if an aerospace vehicle designed to withstand a particular value of peak wind speed at the 18.3-m reference level is exposed to that peak wind speed, the vehicle has at least a 99.865-percent chance of withstanding possible peak wind profile conditions.

Operational ground wind constraints for established vehicles should be determined for a reference level (above natural grade) near the top of the vehicle while on the launch pad. The profile may be calculated using equations (2.1) and (2.2) with a value of $k = \bar{k} + 3\,\sigma$. This will produce a peak wind profile envelope associated with an upper reference level ground wind constraint.

Table 2-2 contains peak wind speed profiles for various envelope values of peak wind speed at the 10-m level for fixed values of risk for the worst monthly-hourly reference periods of the year for a 1-hour exposure. To construct these profiles, the 1-hour exposure period statistics for each hour in each month were constructed. This exercise yielded 288 distribution functions (12 months times 24 hours), which were enveloped to yield the largest or “worst” 10-m level peak wind speed associated with a given level of risk for all monthly-hourly reference periods. Thus, for example, according to Table 2-2 there is at most a 10-percent risk that the peak wind speed will exceed 13.9 m/s (27.0 knots) during any particular hour in any particular month at the 10-m level; and if a peak wind speed equal to 13.9 m/s (27.0 knots) should occur at the 10-m level, then there is only a 0.135-percent chance that the peak wind speed will exceed 24.1 m/s (46.8 knots) at the 152.4-m level or the corresponding values given at the other heights.

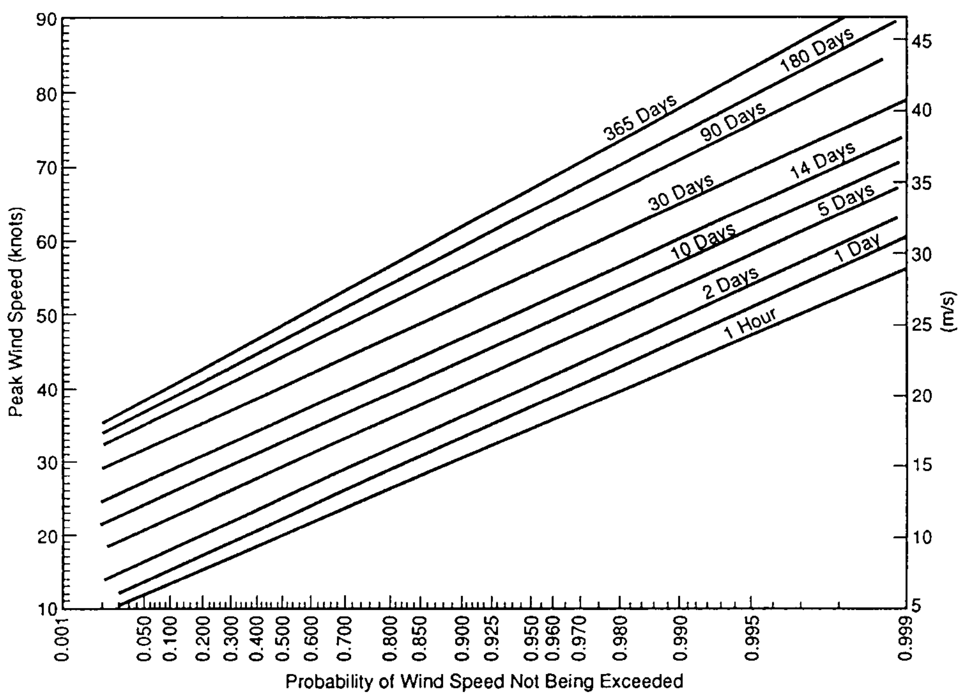



FIGURE 2-3. <u>18.3-M Reference Level; KSC Peak Wind Speed for Windiest Reference Period Versus Probability for Several Exposure Periods Applicable to Vehicle Design Criteria Development.</u>

TABLE 2-2. Peak Wind Speed Profile Envelopes for Various Values of Risk of Exceeding the 10-m Level Peak Wind Speed for 1-H Exposure (Hourly-Monthly Reference Period) for KSC.

| Height | | Risk (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | | 10 | | 5 | | 1 | | 0.1 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 22.9 | 11.8 | 27.0 | 13.9 | 30.8 | 15.8 | 39.5 | 20.3 | 51.9 | 26.7 |
| 18.3 | 60 | 26.3 | 13.5 | 30.5 | 15.7 | 34.4 | 17.7 | 43.4 | 22.3 | 56.0 | 28.8 |
| 30.5 | 100 | 29.5 | 15.2 | 33.8 | 17.4 | 37.9 | 19.5 | 47.0 | 24.2 | 59.8 | 30.8 |
| 61.0 | 200 | 34.5 | 17.8 | 38.9 | 20.0 | 43.0 | 22.1 | 52.3 | 26.9 | 65.5 | 33.6 |
| 91.4 | 300 | 37.8 | 19.5 | 42.2 | 21.7 | 46.4 | 23.9 | 55.7 | 28.7 | 68.9 | 35.4 |
| 121.9 | 400 | 40.4 | 20.8 | 44.7 | 23.0 | 48.9 | 25.2 | 58.3 | 30.0 | 71.5 | 36.8 |
| 152.4 | 500 | 42.5 | 21.9 | 46.8 | 24.1 | 51.0 | 26.2 | 60.3 | 31.0 | 73.6 | 37.8 |

Tables 2-3 through 2-5 contain peak wind speed profile envelopes for various values of peak wind speed at the 10-m level and fixed values of risk for various exposure periods, The 1-day exposure values of peak wind speed were obtained by constructing the daily peak wind statistics for each month and then enveloping these distributions to yield the worst 1-day exposure, 10-m level peak wind speed for a specified value of risk (daily-monthly reference period). The 30-day exposure envelope peak wind speeds were obtained by constructing the monthly peak wind statistics for each month and then constructing the envelope of the distributions (monthly-annual reference period). The 10-day exposure statistics were obtained by interpolating between the 1- and 30-day exposure period results. The envelopes of the 90-day exposure period statistics are the 90-day exposure statistics associated with the 12 trimonthly periods (January-February-March, February-March-April, March-April-May, and so forth) (90-day-annual reference period). Finally, the 365-day exposure period statistics were calculated with the annual peak wind sample (17 data points) to yield one distribution. Tables 2-3 through 2-5 contain the largest or “worst” 10-m level peak wind speed associated with a given level of risk for the stated exposure periods.

TABLE 2-3. Peak Wind Speed Envelopes for A 10-Percent Risk, Value of Exceeding The 10-m Level Peak Wind Speed for Various Reference Periods of Exposure for KSC

| Height | | Exposure (Days) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 10 | | 30 | | 90 | | 365 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 29.6 | 15.2 | 39.8 | 20.5 | 47.1 | 24.3 | 52.0 | 26.8 | 57.4 | 29.5 |
| 18.3 | 60 | 33.2 | 17.1 | 43.7 | 22.5 | 51.2 | 26.4 | 56.2 | 28.9 | 61.7 | 31.8 |
| 30.5 | 100 | 36.6 | 18.8 | 47.3 | 24.3 | 54.9 | 28.3 | 60.0 | 30.9 | 65.6 | 33.8 |
| 61.0 | 200 | 41.8 | 21.5 | 52.7 | 27.1 | 60.4 | 31.1 | 65.6 | 33.8 | 71.3 | 36.7 |
| 91.4 | 300 | 45.1 | 23.2 | 56.1 | 28.9 | 63.9 | 32.9 | 69.1 | 35.6 | 74.8 | 38.5 |
| 121.9 | 400 | 47.6 | 24.5 | 58.6 | 30.2 | 66.5 | 34.2 | 71.7 | 36.9 | 77.4 | 39.8 |
| 152.4 | 500 | 49.7 | 25.6 | 60.7 | 31.2 | 68.5 | 35.3 | 73.8 | 38.0 | 79.5 | 40.9 |

TABLE 2-4. Peak Wind Speed Profile Envelopes for a 5-Percent Risk Value of Exceeding the 10-m Level Peak Wind Speed for Various Reference Periods of Exposure for KSC.

| Height | | Exposure (Days) 1 | | 10 | | 30 | | 90 | | 365 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 33.7 | 17.3 | 43.9 | 22.6 | 51.2 | 26.4 | 56.4 | 29.0 | 62.3 | 32.1 |
| 18.3 | 60 | 37.4 | 19.3 | 47.9 | 24.7 | 55.4 | 28.5 | 60.7 | 31.2 | 66.7 | 34.3 |
| 30.5 | 100 | 40.9 | 21.0 | 51.6 | 26.5 | 59.2 | 30.5 | 64.6 | 33.2 | 70.7 | 36.4 |
| 61.0 | 200 | 46.1 | 23.7 | 57.0 | 29.3 | 64.8 | 33.3 | 70.2 | 36.2 | 76.4 | 39.3 |
| 91.4 | 300 | 49.5 | 25.5 | 60.4 | 31.1 | 68.2 | 35.1 | 73.7 | 38.0 | 80.0 | 41.2 |
| 121.9 | 400 | 52.0 | 26.8 | 63.0 | 32.4 | 70.8 | 36.5 | 76.4 | 39.3 | 82.6 | 42.5 |
| 152.4 | 500 | 54.1 | 27.8 | 65.1 | 33.5 | 72.9 | 37.5 | 78.5 | 40.4 | 84.7 | 43.6 |

TABLE 2-5. Peak Wind Speed Profile Envelopes for A 1-Percent Risk Value of Exceeding the 10-mLevel Peak wind Speed for Various Reference Periods of Exposure for KSC.

| Height | | Exposure (Days) 1 | | 10 | | 30 | | 90 | | 365 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 43.0 | 22.1 | 53.3 | 27.4 | 60.6 | 31.2 | 66.5 | 34.2 | 73.4 | 37.8 |
| 18.3 | 60 | 47.0 | 24.2 | 57.5 | 29.6 | 65.0 | 33.5 | 71.0 | 36.6 | 78.0 | 40.2 |
| 30.5 | 100 | 50.7 | 26.1 | 61.3 | 31.6 | 68.9 | 35.5 | 75.0 | 38.6 | 82.1 | 42.3 |
| 61.0 | 200 | 56.1 | 28.9 | 66.9 | 34.5 | 74.7 | 38.4 | 80.8 | 41.6 | 88.0 | 45.3 |
| 91.4 | 300 | 59.5 | 30.6 | 70.4 | 36.3 | 78.2 | 40.3 | 84.4 | 43.5 | 91.7 | 47.2 |
| 121.9 | 400 | 62.1 | 32.0 | 73.0 | 37.6 | 80.8 | 41.6 | 87.1 | 44.8 | 94.3 | 48.6 |
| 152.4 | 500 | 64.1 | 33.0 | 75.1 | 38.7 | 82.9 | 42.7 | 89.2 | 45.9 | 96.5 | 49.7 |

It is recommended that the data in Tables 2-2 through 2-5 be used as the basis for aerospace vehicle design for KSC operations. Wind profile statistics for the design of permanent ground support equipment are discussed in subsection 2.2.10.

Mean wind profiles or steady-state wind profiles can be obtained from the peak wind profiles by dividing the peak wind by the appropriate gust factor (subsection 2.2.7). It is recommended that the 10-min gust factors be used for structural design purposes. Application of the 10-min gust factors to the peak wind profile corresponds to averaging the wind speed over a 10-min period. This averaging period appears to result in a sTable mean value of the wind speed. Within the range of variation of the data, the 1-h and 10-min gust factors are approximately equal for sufficiently high wind speed. This occurs because the spectrum of the horizontal wind speed near the ground is characterized by a broad energy gap centered at a frequency approximately equal to 0.000278 Hz (1 cycle/h) and typically extends over the frequency domain 0.000139 Hz (0.5 cycles/h) $< \omega <$ 0.0014 Hz (5 cycles/h). The Fourier spectral components associated with frequencies less than 0.000278 Hz (1 cycle/h) correspond to the meso- and synoptic-scale atmospheric motions, while the remaining high-frequency spectral components correspond to mechanically and thermally produced turbulence. Thus, a statistically stable estimate of the mean or steady-state wind speed can be obtained by averaging over a period in the range from 10 min to an hour. Since this period is far longer than any natural period of structural vibration, it assures that effects caused by the mean wind properly represent steady-state, nontransient effects. The steady-state wind profiles, calculated with the 10-min gust factors, that correspond to those in Tables 2-2 through 2-5, are given in Tables 2-6 through 2-9.

TABLE 2-6. 10-Min Mean Wind Speed Profile Envelopes for Various Values of Risk of Exceeding the 10-m Level Mean Wind Speed for a 1-h Exposure (Hourly-Monthly Reference Period) for KSC

| Height | | Risk (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | | 10 | | 5 | | 1 | | 0.1 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 14.1 | 7.2 | 16.6 | 8.6 | 19.1 | 9.8 | 24.6 | 12.7 | 32.4 | 16.7 |
| 18.3 | 60 | 17.1 | 8.8 | 19.9 | 10.3 | 22.6 | 11.7 | 28.7 | 14.8 | 37.2 | 19.1 |
| 30.5 | 100 | 20.0 | 10.3 | 23.1 | 11.9 | 26.0 | 13.4 | 32.6 | 16.8 | 41.6 | 21.4 |
| 61.0 | 200 | 24.7 | 12.7 | 28.1 | 14.5 | 31.3 | 16.1 | 38.3 | 19.7 | 48.1 | 24.7 |
| 91.4 | 300 | 27.8 | 14.3 | 31.3 | 16.1 | 34.7 | 17.9 | 42.0 | 21.6 | 52.1 | 26.8 |
| 121.9 | 400 | 30.3 | 15.6 | 33.9 | 17.4 | 37.3 | 19.2 | 44.8 | 23.0 | 55.1 | 28.3 |
| 152.4 | 500 | 32.3 | 16.6 | 35.9 | 18.5 | 39.4 | 20.3 | 47.0 | 24.2 | 57.5 | 29.6 |

TABLE 2-7. 10-Min Mean Wind Speed Profile Envelopes for a 10-Percent Risk Value of Exceeding the 10-mLevel mean Wind Speed for Various Reference Periods of Exposure for KSC.

| Height | | Exposure (Days) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 10 | | 30 | | 90 | | 365 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 18.3 | 9.4 | 24.8 | 12.8 | 29.4 | 15.1 | 32.5 | 16.7 | 35.9 | 18.5 |
| 18.3 | 60 | 21.8 | 11.2 | 28.9 | 14.9 | 34.0 | 17.5 | 37.3 | 19.2 | 41.0 | 21.1 |
| 30.5 | 100 | 25.2 | 12.9 | 32.8 | 16.9 | 38.1 | 19.6 | 41.7 | 21.5 | 45.6 | 23.5 |
| 61.0 | 200 | 30.3 | 15.6 | 38.6 | 19.9 | 44.3 | 22.8 | 48.2 | 24.8 | 52.4 | 27.0 |
| 91.4 | 300 | 33.7 | 17.3 | 42.3 | 21.8 | 48.3 | 24.8 | 52.2 | 26.9 | 56.6 | 29.1 |
| 121.9 | 400 | 36.3 | 18.7 | 45.0 | 23.2 | 51.2 | 26.3 | 55.2 | 28.4 | 59.7 | 30.7 |
| 152.4 | 500 | 38.4 | 19.7 | 47.3 | 24.3 | 53.5 | 27.6 | 57.6 | 29.7 | 62.2 | 32.0 |

TABLE 2-8. 10-Min Mean Wind Speed Profile Envelopes for a 5-Percent Risk of Exceeding the 10-m Level Mean Wind Speed for Various Reference Periods of Exposure For KSC.

| Height | | Exposure (Days) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 10 | | 30 | | 90 | | 365 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 20.9 | 10.8 | 27.4 | 14.1 | 32.0 | 16.5 | 35.3 | 18.2 | 39.0 | 20.1 |
| 18.3 | 60 | 24.7 | 12.7 | 31.8 | 16.3 | 36.8 | 18.9 | 40.3 | 20.7 | 44.3 | 22.8 |
| 30.5 | 100 | 28.2 | 14.5 | 35.8 | 18.4 | 41.1 | 21.2 | 44.9 | 23.1 | 49.1 | 25.3 |
| 61.0 | 200 | 33.6 | 17.3 | 41.8 | 21.5 | 47.6 | 24.5 | 51.6 | 26.6 | 56.2 | 28.9 |
| 91.4 | 300 | 37.1 | 19.1 | 45.6 | 23.5 | 51.6 | 26.6 | 55.8 | 28.7 | 60.5 | 31.2 |
| 121.9 | 400 | 39.8 | 20.5 | 48.5 | 25.0 | 54.6 | 28.1 | 58.9 | 30.3 | 63.7 | 32.8 |
| 152.4 | 500 | 42.0 | 21.6 | 50.8 | 26.1 | 57.0 | 29.3 | 61.4 | 31.6 | 66.3 | 34.1 |

TABLE 2-9. 10-Min Mean Wind Speed Profile Envelopes for a 1-Percent Risk Value of Exceeding the 10-m Level Mean Wind Speed for Various Reference Periods ..of Exposure for KSC.

| Height | | Exposure (Days) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 10 | | 30 | | 90 | | 365 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 26.8 | 13.8 | 33.3 | 17.1 | 37.9 | 19.5 | 41.6 | 21.4 | 45.9 | 23.6 |
| 18.3 | 60 | 31.1 | 16.0 | 38.2 | 19.7 | 43.2 | 22.2 | 47.2 | 24.3 | 51.8 | 26.7 |
| 30.5 | 100 | 35.1 | 18.1 | 42.6 | 21.9 | 47.9 | 24.7 | 52.2 | 26.9 | 57.1 | 29.4 |
| 61.0 | 200 | 41.1 | 21.2 | 49.2 | 25.3 | 54.9 | 28.3 | 59.4 | 30.6 | 64.7 | 33.2 |
| 91.4 | 300 | 44.9 | 23.1 | 53.3 | 27.4 | 59.2 | 30.5 | 63.9 | 32.9 | 69.4 | 35.7 |
| 121.9 | 400 | 47.7 | 24.6 | 56.3 | 29.0 | 62.4 | 32.1 | 67.2 | 34.6 | 72.8 | 37.5 |
| 152.4 | 500 | 50.0 | 25.8 | 58.7 | 30.2 | 64.9 | 33.4 | 69.8 | 35.9 | 75.5 | 38.9 |

2.2.5.5.2 Design Ground Wind Profiles for Other Locations. Tables 2-10 through 2-17 contain recommended design ground wind profiles for several different risks of exceeding the 10-m level peak wind speed and 10-min mean wind speed for a 1-h exposure period. These tables are based on the same philosophy as Table 2-2 and Table 2-6 for KSC. The locations for which data are provided include Stennis Space Center, MS; VAFB, CA; White Sands Missile Range, NM; and Edwards Air Force Base (EAFB), CA.

TABLE 2-10. Surface Peak Wind Speed Profile Envelopes for Various Values of Risk of Exceeding the 10-m Level Peak Wind Speed for 1-h Exposure (Hourly-Monthly Reference Period) for the Stennis Space Center Area.

| Height | | Risk (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | | 10 | | 5 | | 1 | | 0.1 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 19.8 | 10.2 | 23.9 | 12.3 | 27.6 | 14.2 | 37.2 | 19.1 | 53.0 | 27.3 |
| 18.3 | 60 | 22.4 | 11.5 | 27.0 | 13.9 | 31.2 | 16.0 | 42.0 | 21.5 | 57.7 | 29.7 |
| 30.5 | 100 | 24.8 | 12.8 | 29.9 | 15.4 | 34.5 | 17.8 | 46.5 | 23.9 | 61.9 | 31.8 |
| 61.0 | 200 | 28.4 | 14.6 | 34.3 | 17.7 | 39.6 | 20.4 | 53.4 | 27.4 | 68.1 | 35.1 |
| 91.4 | 300 | 30.8 | 15.9 | 37.2 | 19.2 | 43.0 | 22.1 | 57.9 | 29.8 | 72.2 | 37.2 |
| 121.9 | 400 | 32.7 | 16.8 | 39.4 | 20.3 | 45.5 | 23.4 | 61.4 | 31.5 | 75.2 | 38.7 |
| 152.4 | 500 | 34.2 | 17.6 | 41.3 | 21.3 | 47.7 | 24.5 | 64.3 | 33.0 | 77.5 | 39.9 |

TABLE 2-11. Surface Mean Wind Speed Profile Envelopes for Various Values of Risk of Exceeding the 10-m Level 10-Min Mean Wind Speed for 1-h Exposure ..(Hourly-Monthly Reference Period) for Stennis Space Center Area.

| Height | | Risk (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | | 10 | | 5 | | 1 | | 0.1 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 14.1 | 7.3 | 17.1 | 8.8 | 19.7 | 10.1 | 26.6 | 13.7 | 37.9 | 19.5 |
| 18.3 | 60 | 16.0 | 8.2 | 19.3 | 9.9 | 22.3 | 11.4 | 30.0 | 15.4 | 41.2 | 21.2 |
| 30.5 | 100 | 17.7 | 9.1 | 21.4 | 11.0 | 24.7 | 12.7 | 33.2 | 17.1 | 44.2 | 22.8 |
| 61.0 | 200 | 20.3 | 10.5 | 24.5 | 12.6 | 28.3 | 14.6 | 38.2 | 19.6 | 48.6 | 25.0 |
| 91.4 | 300 | 22.0 | 11.3 | 26.6 | 13.7 | 30.7 | 15.8 | 41.4 | 21.3 | 51.0 | 26.6 |
| 121.9 | 400 | 23.3 | 12.0 | 28.2 | 14.5 | 32.5 | 16.7 | 43.8 | 22.5 | 53.7 | 27.7 |
| 152.4 | 500 | 24.4 | 12.6 | 29.5 | 15.2 | 34.1 | 17.5 | 45.9 | 23.6 | 55.4 | 28.5 |

TABLE 2-12. Surface Peak Wind Speed Profile Envelopes for Various Values of Risk of Exceeding the 10-m Level Peak Wind Speed for 1-h Exposure (Hourly-Monthly Reference Period) for VAFB, CA.

| Height | | Risk (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | | 10 | | 5 | | 1 | | 0.1 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 20.0 | 10.3 | 23.8 | 12.3 | 27.5 | 14.2 | 35.8 | 18.4 | 47.3 | 24.3 |
| 18.3 | 60 | 22.5 | 11.6 | 26.8 | 13.8 | 31.0 | 16.0 | 40.3 | 20.8 | 51.4 | 26.5 |
| 30.5 | 100 | 25.0 | 12.9 | 29.7 | 15.3 | 34.3 | 17.7 | 44.7 | 23.0 | 55.2 | 28.5 |
| 61.0 | 200 | 28.7 | 14.8 | 34.1 | 17.6 | 39.4 | 20.3 | 51.3 | 26.4 | 60.9 | 31.3 |
| 91.4 | 300 | 31.1 | 16.0 | 37.0 | 19.0 | 42.8 | 22.0 | 56.7 | 28.7 | 64.4 | 33.2 |
| 121.9 | 400 | 32.9 | 16.9 | 39.2 | 20.2 | 45.3 | 23.3 | 59.0 | 30.4 | 67.1 | 34.5 |
| 152.4 | 500 | 34.4 | 17.7 | 41.0 | 21.1 | 47.4 | 24.4 | 61.7 | 31.7 | 69.2 | 35.6 |

TABLE 2-13. Surface Mean Wind Speed Profile Envelopes for Various Values of Risk of Exceeding the 10-m Level 10-Min Mean Wind Speed for 1-h Exposure (Hourly-Monthly Reference Period) for VAFB, CA.

| Height | | Risk (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | | 10 | | 5 | | 1 | | 0.1 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 14.3 | 7.4 | 17.0 | 8.9 | 19.6 | 10.1 | 25.6 | 13.1 | 33.8 | 17.4 |
| 18.3 | 60 | 16.1 | 8.3 | 19.2 | 9.9 | 22.1 | 11.4 | 28.8 | 14.8 | 36.7 | 18.9 |
| 30.5 | 100 | 17.8 | 9.2 | 21.2 | 10.9 | 24.5 | 12.6 | 31.9 | 16.4 | 39.5 | 20.3 |
| 61.0 | 200 | 20.5 | 10.5 | 24.4 | 12.6 | 28.1 | 14.5 | 36.7 | 18.9 | 43.5 | 22.4 |
| 91.4 | 300 | 22.2 | 11.4 | 26.4 | 13.6 | 30.5 | 15.7 | 39.8 | 20.5 | 46.0 | 23.7 |
| 121.9 | 400 | 23.5 | 12.1 | 28.0 | 14.4 | 32.3 | 16.7 | 42.1 | 21.7 | 17.9 | 24.7 |
| 152.4 | 500 | 24.6 | 12.7 | 29.3 | 15.1 | 33.8 | 17.4 | 44.0 | 22.7 | 49.4 | 25.5 |

TABLE 2-14. Surface Peak Wind Speed Profile Envelopes For Various Values Of Risk Of Exceeding The 10-m Level Peak Wind Speed for 1-h Exposure (Hourly-Monthly Reference Period) For White Sands Missile Range, NM.

| Height | | Risk (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | | 10 | | 5 | | 1 | | 0.1 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 15.3 | 7.9 | 20.9 | 10.7 | 24.7 | 12.7 | 34.3 | 17.7 | 52.1 | 26.8 |
| 18.3 | 60 | 17.3 | 8.9 | 23.6 | 12.1 | 27.9 | 14.3 | 38.8 | 20.0 | 56.7 | 29.2 |
| 30.5 | 100 | 19.1 | 9.9 | 26.1 | 13.4 | 30.9 | 15.9 | 42.9 | 22.1 | 60.9 | 31.3 |
| 61.0 | 200 | 22.0 | 11.3 | 30.0 | 15.4 | 35.5 | 18.2 | 49.3 | 25.4 | 66.9 | 34.4 |
| 91.4 | 300 | 23.8 | 12.3 | 32.6 | 16.7 | 38.5 | 19.8 | 53.4 | 27.6 | 71.0 | 36.5 |
| 121.9 | 400 | 25.2 | 13.0 | 34.5 | 17.7 | 40.8 | 21.0 | 56.6 | 29.2 | 73.9 | 38.0 |
| 152.4 | 500 | 26.4 | 13.7 | 36.1 | 18.5 | 42.7 | 22.0 | 59.3 | 30.6 | 76.2 | 39.2 |

TABLE 2-15. Surface Mean Wind Speed Profile Envelopes For Various Values of Risk of Exceeding The 10-m Level 10-Min Mean Wind Speed For 1-h Exposure (Hourly-Monthly Reference Period) For White Sands Missile Range, NM.

| Height | | Risk (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | | 10 | | 5 | | 1 | | 0.1 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 10.9 | 5.6 | 14.9 | 7.7 | 17.6 | 9.1 | 24.5 | 12.6 | 37.2 | 19.2 |
| 18.3 | 60 | 12.3 | 6.4 | 16.9 | 8.6 | 19.9 | 10.2 | 27.7 | 14.3 | 40.5 | 20.8 |
| 30.5 | 100 | 13.7 | 7.1 | 18.7 | 9.6 | 22.1 | 11.3 | 30.7 | 15.8 | 43.4 | 22.4 |
| 61.0 | 200 | 15.7 | 8.1 | 21.4 | 11.0 | 25.3 | 13.0 | 35.2 | 18.2 | 47.8 | 24.6 |
| 91.4 | 300 | 17.0 | 8.8 | 23.3 | 11.9 | 27.5 | 14.1 | 38.2 | 19.7 | 50.7 | 26.1 |
| 121.9 | 400 | 18.0 | 9.3 | 24.6 | 12.6 | 29.1 | 15.0 | 40.4 | 20.9 | 52.8 | 27.1 |
| 152.4 | 500 | 18.9 | 9.8 | 25.8 | 13.2 | 30.5 | 15.7 | 42.3 | 21.9 | 54.4 | 28.0 |

TABLE 2-16. Surface Peak Wind Speed Profile Envelopes for Various Values of Risk of Exceeding the 10-m Level Peak Wind Speed for 1-h Exposure (Hourly-Monthly Reference Period) for EAFB, CA.

| Height | | Risk (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | | 10 | | 5 | | 1 | | 0.1 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 27.7 | 14.3 | 32.7 | 16.8 | 37.9 | 19.5 | 48.5 | 24.9 | 63.9 | 32.9 |
| 18.3 | 60 | 29.2 | 15.0 | 34.4 | 17.7 | 39.9 | 20.5 | 51.0 | 26.2 | 67.2 | 34.6 |
| 30.5 | 100 | 30.4 | 15.7 | 35.9 | 18.5 | 41.6 | 21.4 | 53.3 | 27.4 | 70.2 | 36.1 |
| 61.0 | 200 | 32.3 | 16.6 | 38.1 | 19.6 | 44.2 | 22.7 | 56.5 | 29.1 | 74.4 | 38.3 |
| 91.4 | 300 | 33.4 | 17.2 | 39.4 | 20.3 | 45.7 | 23.5 | 58.5 | 30.1 | 77.0 | 39.6 |
| 121.9 | 400 | 34.3 | 17.6 | 40.4 | 20.8 | 46.8 | 24.1 | 59.9 | 30.8 | 78.9 | 40.6 |
| 152.4 | 500 | 34.9 | 18.0 | 41.2 | 21.2 | 47.7 | 24.6 | 61.1 | 31.4 | 80.5 | 41.4 |

TABLE 2-17. Surface Mean Wind Speed Profile Envelopes for Various Values of Risk of Exceeding the 10-m Level 10-Min Mean Wind Speed for 1-h Exposure (Hourly-Monthly Reference Period) for EAFB, CA.

| Height | | Risk (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 | | 10 | | 5 | | 1 | | 0.1 | |
| (m) | (ft) | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ | knots | $ms^{-1}$ |
| 10.0 | 33 | 19.6 | 10.1 | 24.6 | 12.7 | 30.0 | 15.4 | 41.4 | 21.3 | 57.9 | 29.8 |
| 18.3 | 60 | 21.1 | 10.8 | 26.4 | 13.6 | 32.1 | 16.5 | 44.1 | 22.7 | 61.5 | 31.6 |
| 30.5 | 100 | 22.4 | 11.5 | 28.0 | 14.4 | 34.0 | 17.5 | 46.5 | 23.9 | 64.7 | 33.3 |
| 61.0 | 200 | 24.2 | 12.5 | 30.3 | 15.6 | 36.7 | 18.9 | 50.0 | 25.7 | 69.2 | 35.6 |
| 91.4 | 300 | 25.4 | 13.1 | 31.7 | 16.3 | 38.4 | 19.7 | 52.2 | 26.8 | 72.0 | 37.0 |
| 121.9 | 400 | 26.2 | 13.5 | 32.7 | 16.8 | 39.6 | 20.4 | 53.7 | 27.6 | 74.0 | 38.1 |
| 152.4 | 500 | 26.9 | 13.8 | 33.5 | 17.2 | 40.5 | 20.9 | 55.0 | 28.3 | 75.6 | 38.9 |

The peak/mean wind profiles were constructed with a 1.4 gust factor and mean $+3\sigma$ value of $k$, as given in subsection 2.2.5.4. Some additional general ground wind data are given in references 2-3 and 2-4 for several other locations.

2.2.5.5.3 Frequency of Reported Calm Winds. Generally, aerospace vehicle design criteria wind problems are concerned with high wind speeds, but a condition of calm or very low speeds (generally < 1 kt) may also be important. For example, with no wind to disperse venting vapors such as LOX, a poor visibility situation could develop around the vehicle. Calm wind conditions can also have significant implications relative to the atmospheric diffusion of vehicle exhaust clouds. In addition, calm wind in conjunction with high solar heating can result in significantly high vehicle compartment temperatures. Table 2-18 shows the frequency of calm winds at the 10-m level for KSC as a function of time of day and month. The maximum percentage of calms appears in the summer and during the early morning hours, with the minimum percentage appearing throughout the year during the afternoon. Similar tables for other locations can be generated upon request.

TABLE 2-18. Frequency (Percent) of Reported Calm Wind at the 10-m Level for KSC.

| Hour | MONTH | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (EST) | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Ann. |
| 00 | 4.8 | 4.0 | 3.6 | 1.3 | 7.3 | 9.2 | 11.7 | 13.7 | 6.3 | 6.9 | 6.3 | 6.0 | 6.8 |
| 01 | 2.8 | 1.3 | 2.4 | 1.7 | 8.9 | 8.3 | 10.9 | 14.1 | 7.1 | 4.8 | 6.3 | 6.5 | 6.3 |
| 02 | 4.8 | 2.2 | 3.6 | 2.9 | 7.7 | 10.0 | 11.7 | 13.7 | 10.4 | 7.3 | 5.4 | 4.0 | 7.0 |
| 03 | 5.2 | 3.1 | 2.0 | 3.8 | 8.5 | 12.1 | 11.3 | 17.3 | 12.1 | 5.2 | 2.9 | 3.2 | 7.3 |
| 04 | 2.8 | 4.4 | 2.4 | 3.8 | 5.2 | 13.8 | 14.5 | 13.7 | 10.8 | 5.2 | 4.6 | 2.8 | 7.0 |
| 05 | 4.4 | 4.0 | 3.2 | 2.9 | 9.7 | 16.3 | 15.3 | 18.5 | 13.3 | 3.6 | 4.6 | 4.4 | 8.4 |
| 06 | 4.4 | 4.0 | 4.4 | 2.9 | 8.9 | 16.3 | 19.8 | 19.0 | 13.3 | 3.2 | 5.0 | 5.2 | 8.9 |
| 07 | 3.6 | 4.4 | 4.8 | 6.3 | 10.5 | 16.7 | 18.1 | 19.4 | 15.8 | 4.4 | 5.4 | 5.6 | 9.6 |
| 08 | 3.6 | 6.6 | 6.5 | 2.9 | 2.4 | 5.4 | 6.0 | 6.9 | 4.6 | 4.0 | 8.8 | 4.4 | 5.2 |
| 09 | 3.6 | 1.8 | 2.0 | 2.1 | 2.8 | 3.8 | 4.8 | 1.6 | 4.2 | 0.8 | 4.6 | 5.6 | 3.1 |
| 10 | 0.4 | 1.8 | 1.6 | 1.7 | 0.4 | 3.8 | 4.0 | 2.8 | 2.1 | * | 1.3 | 2.4 | 1.8 |
| 11 | 0.4 | 1.3 | 1.2 | 1.7 | 0.8 | 1.3 | 2.4 | 0.8 | 2.9 | 0.8 | 1.7 | 0.8 | 1.3 |
| 12 | 1.6 | 0.4 | * | * | * | 0.8 | 0.8 | 0.4 | 1.3 | 0.4 | 2.1 | 1.2 | 0.8 |
| 13 | 2.0 | 0.4 | * | * | 0.4 | 1.3 | 0.4 | 1.6 | 0.8 | 0.4 | 1.7 | 0.4 | 0.8 |
| 14 | 0.8 | 4.0 | 0.8 | 0.4 | 0.4 | 0.8 | 1.2 | 1.6 | 1.3 | 0.8 | * | 0.4 | 0.7 |
| 15 | 0.4 | 1.3 | * | * | * | 0.8 | 0.4 | 1.6 | 2.5 | 0.4 | 0.4 | 0.4 | 0.7 |
| 16 | 0.4 | 0.4 | 0.4 | * | 0.8 | 0.4 | 0.8 | 0.4 | 1.3 | 0.8 | * | 0.8 | 0.5 |
| 17 | 1.6 | 0.4 | * | 0.4 | 0.4 | 2.1 | 0.8 | 3.2 | 2.1 | 1.6 | 1.7 | 2.0 | 1.4 |
| 18 | 4.0 | 1.8 | 0.8 | 0.4 | 1.6 | 2.5 | 3.2 | 4.0 | 2.9 | 1.2 | 5.0 | 7.7 | 2.9 |
| 19 | 2.8 | 3.5 | 2.0 | * | 1.6 | 5.0 | 2.8 | 5.2 | 4.6 | 1.2 | 7.1 | 6.5 | 3.5 |
| 20 | 4.4 | 3.5 | 2.8 | 1.7 | 3.2 | 6.7 | 5.6 | 8.5 | 7.5 | 1.6 | 6.3 | 6.0 | 4.8 |
| 21 | 5.2 | 4.0 | 3.2 | 1.3 | 4.8 | 7.5 | 10.5 | 8.9 | 8.3 | 4.4 | 5.0 | 6.0 | 5.8 |
| 22 | 3.6 | 2.2 | 2.4 | 1.7 | 6.0 | 7.5 | 7.7 | 12.9 | 7.9 | 4.8 | 6.3 | 5.2 | 5.7 |
| 23 | 5.6 | 3.5 | 4.8 | 0.8 | 6.5 | 8.3 | 10.5 | 15.3 | 10.0 | 5.6 | 4.6 | 5.2 | 6.8 |
| All Hours | 3.1 | 2.5 | 2.3 | 1.7 | 4.1 | 6.7 | 7.3 | 8.6 | 6.4 | 2.9 | 4.0 | 3.9 | 4.5 |

2.2.6 Spectral Ground Wind Turbulence Model. Under most conditions, ground winds are fully developed turbulent flows. This is particularly true when the wind speed is greater than a few meters per second or the atmosphere is unstable, and especially when both conditions exist. During nighttime conditions when the wind speed is typically low and the stratification is stable, the intensity of turbulence is small if not nil. Spectral methods are a particularly useful way of representing the turbulent portion of the ground wind environment for launch vehicle design purposes, as well as for use in diffusion calculations of toxic fuels and atmospheric pollutants.

2.2.6.1 Introduction. At a fixed point in the atmospheric boundary layer, the instantaneous wind vector from the quasi-steady wind vector is the horizontal vector component of turbulence. This vector departure can be represented by two components, the longitudinal and the lateral components of turbulence which are parallel and perpendicular to the steady-state wind vector in the horizontal plane (Fig. 2-4). The model contained herein is a spectral representation of the characteristics of the longitudinal and lateral components of turbulence. The model analytically defines the spectra of these components of turbulence for the first 200 m of the boundary layer. In addition, it defines the longitudinal and lateral cospectra, quadrature spectra, and corresponding coherence functions associated with any pair of levels in the boundary space. Details concerning the model can be found in references 2-5 through 2-8.

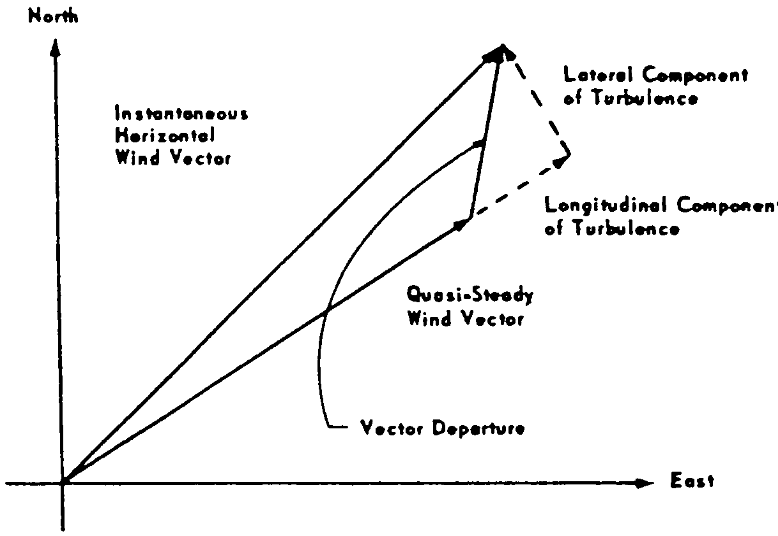



FIGURE 2-4. The Relationship Between the Quasi-Steady State and the Horizontal Instantaneous Wind Vectors and the Longitudinal and Lateral Components of Turbulence.

2.2.6.2 Turbulence Spectra. The longitudinal and lateral spectra of turbulence at frequency ?, and height $z$ can be represented by a dimensionless function of the form

$$\frac{w S(w)}{b\ u_*^2} = \frac{C_1 f/f_m}{\left[1+1.5\,(f/f_m)^{C_2}\right]^{(5/3)C_2}} \ , \qquad (2.3)$$

where

$$f = \frac{w z}{u(z)} \ , \qquad (2.4)$$

$$f_m = C_3 \left(\frac{z}{z_r}\right)^{C_4} \ , \qquad (2.5)$$

$$b = \left(\frac{z}{z_r}\right)^{C_5} \ , \qquad (2.6)$$

$$u_* = c_6 \overline{u}\,(z_r) \ . \qquad (2.7)$$

In these equations $z_r$ is a reference height equal to 18.3 m (60 ft); $u(z_r)$ is the quasi-steady wind speed at height $z$; and the quantities $c_i$ ($i$ = 1,2,3,4,5) are dimensionless constants that depend upon the site and the atmospheric stability. The frequency, $w$ in units of cycles per unit time, is defined with respect to a structure or vehicle at rest relative to the Earth. The reader is referred to sections 2.3.13 and 2.3.14 for the definition of turbulence spectral inputs for application to the takeoff and landing of conventional aeronautical systems and the landing of the space shuttle orbiter vehicle. The spectrum $S(w)$ is defined so that integration over the domain $0 \leq w \leq \infty$ yields the variance of the turbulence. Engineering values of $c_i$ are given in Table 2-19 for the longitudinal spectrum and in Table 2-20 for the lateral spectrum.

The constant $c_6$ to input into equation (2.7) can be estimated with the equation

$$c_6 = \frac{0.4}{ln\left(\frac{z_r}{z_0}\right) - y}, \qquad (2.8)$$

where $z_0$ is the surface roughness length of the site and $Y$ is a parameter that depends upon the stability. If $z_0$ is not available for a particular site, then an estimate of $z_0$ can be obtained by taking 10 percent of the typical height of the surface obstructions (grass, shrubs, trees, rocks, etc.). The typical height is determined over a fetch (the distance the wind blows over a surface) equal to approximately 1,500 m. The parameter $Y$ vanishes for strong wind conditions and is of order unity for light wind, unstable daytime conditions at KSC. Typical values of $z_0$ for various surfaces are given in Table 2-21.

TABLE 2-19. Dimensionless Constants ($C_i$) For The Longitudinal Spectrum of Turbulence For KSC.

| Conditions | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ |
|---|---|---|---|---|---|
| Light Wind Daytime Conditions | 2.905 | 1.235 | 0.04 | 0.87 | –0.14 |
| Strong Winds | 6.198 | 0.845 | 0.03 | 1.0 | –0.63 |

TABLE 2-20. Dimensionless Constants ($C_i$) for the Lateral Spectrum of Turbulence for KSC.

| Conditions | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ |
|---|---|---|---|---|---|
| Light Wind Daytime Conditions | 4.599 | 1.144 | 0.033 | 0.72 | –0.04 |
| Strong Winds | 3.954 | 0.781 | 0.1 | 0.58 | –0.35 |

TABLE 2-21. Typical Values of Surface Roughness Length ($z_0$) for Various Types of Surfaces.

| Type of Surface | $z_0$ (m) | $z_0$ (ft) |
|---|---|---|
| Mud flats, ice | $10^{-5}$–$3x10^{-5}$ | $3x10^{-5}$–$10^{-4}$ |
| Smooth sea | $2x10^{-4}$–$3x10^{-4}$ | $7x10^{-4}$–$10^{-3}$ |
| Sand | $10^{-4}$–$10^{-3}$ | $3x10^{-4}$–$3x10^{-3}$ |
| Snow surface | $10^{-3}$–$6x10^{-3}$ | $3x10^{-4}$–$2x10^{-2}$ |
| Mown grass (~0.01 m) | $10^{-3}$–$10^{-2}$ | $3x10^{-3}$–$3x10^{-2}$ |
| Low grass, steppe | $10^{-2}$–$4x10^{-2}$ | $3x10^{-2}$–$10^{-1}$ |
| Fallow field | $2x10^{-2}$–$3x10^{-2}$ | $6x10^{-2}$–$10^{-1}$ |
| High grass | $4x10^{-2}$–$10^{-1}$ | $10^{-1}$–$3x10^{-1}$ |
| Palmetto | $10^{-1}$–$3x10^{-1}$ | $3x10^{-1}$–1 |
| Suburbia | 1–2 | 3–6 |
| City | 1–4 | 3–13 |

The function given by equation (2.3) is depicted in figures 2-5 and 2-6. Upon prescribing the steady-state wind profile $u(z)$ and the site $(z_0)$, the longitudinal and lateral spectra are completely specified functions of height, $z$, and frequency, $w$. A discussion of the units of the various parameters mentioned previously is given in subsection 2.2.6.4.

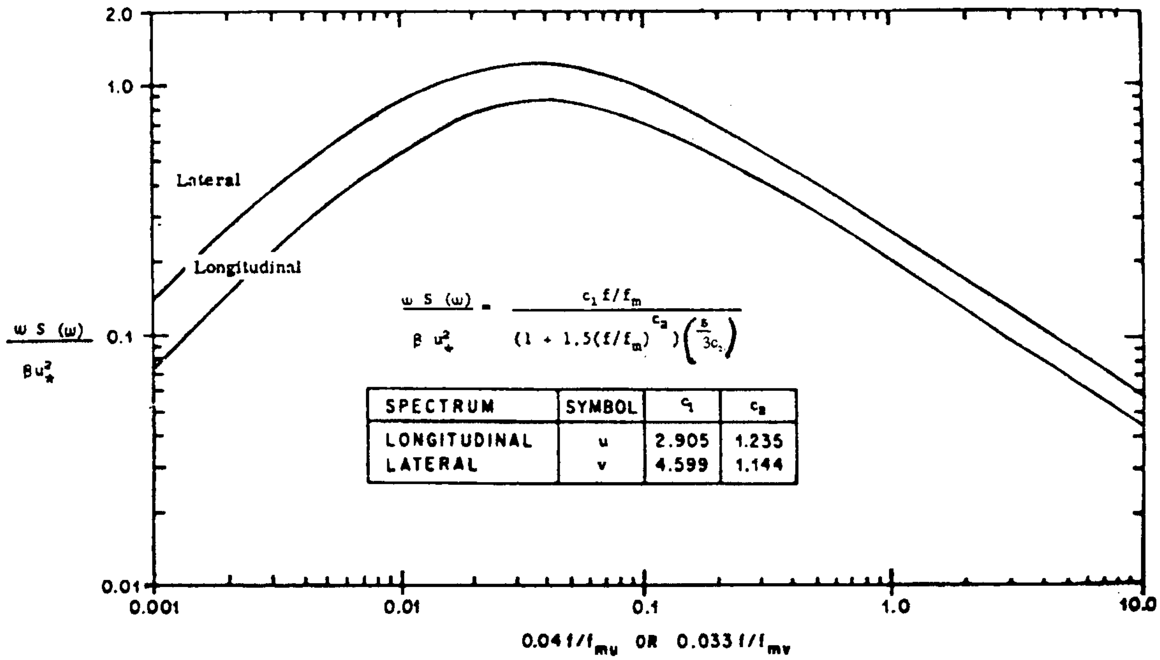



FIGURE 2-5. $\omega S(\omega)/\beta u_*^2$ Versus $0.04 f/f_m$ (Longitudinal) And $0.033 f/f_m$ (Lateral) For Light Wind Daytime Conditions.

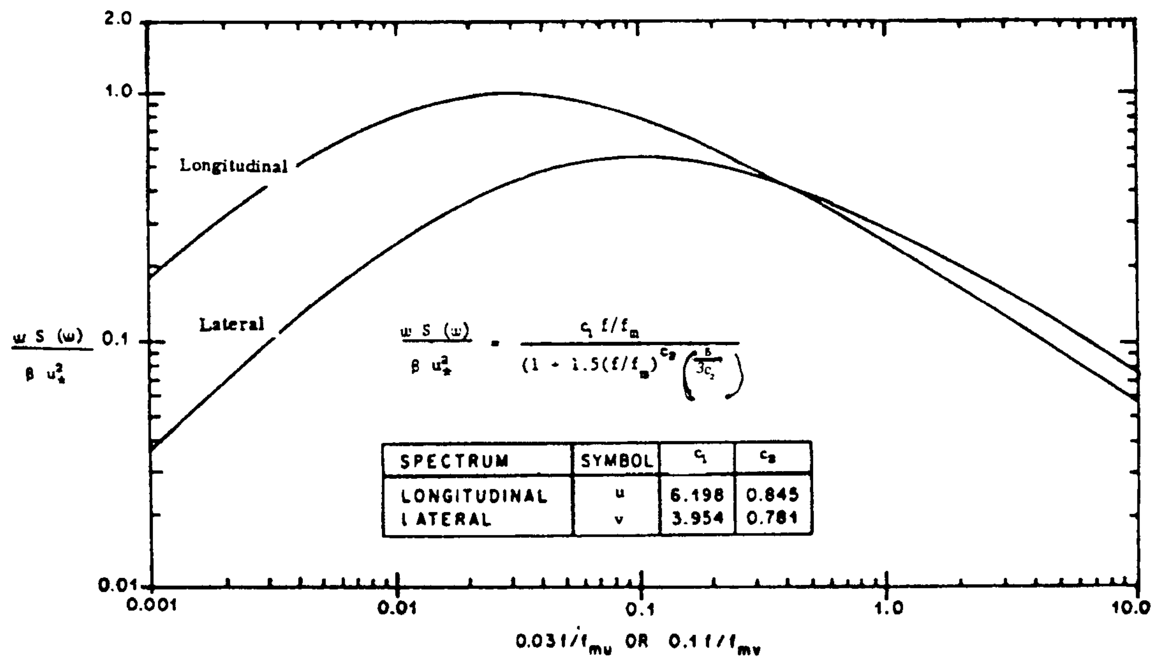



FIGURE 2-6. $\omega S(\omega)/\beta u_*^2$ Versus $0.03 f/f_m$ (Longitudinal) And $0.1 f/f_m$ (Lateral) For Strong Wind Conditions.

2.2.6.3 The Cospectrum and Quadrature Spectrum. The cospectrum ($C$) and the quadrature ($Q$) spectrum associated with either the longitudinal or lateral components of turbulence at levels $z_1$ and $z_2$ can be represented by the following:

$$C(w, z_1, z_2) = \sqrt{S_1 S_2}\, exp\left(-0.3465 \frac{\Delta f}{\Delta f_{0.5}}\right) \cos\,(2pg\,\Delta f)\ , \tag{2.9}$$

$$Q(w, z_1, z_2) = \sqrt{S_1 S_2}\, exp\left(-0.3465 \frac{\Delta f}{\Delta f_{0.5}}\right) \sin\,(2pg\,\Delta f)\ , \tag{2.10}$$

where

$$\Delta f = \frac{w\, z_2}{\overline{u}(z_2)} - \frac{w\, z_1}{\overline{u}(z_1)}\ . \tag{2.11}$$

The quantities $S_1$ and $S_2$ are the longitudinal or lateral spectra at levels $z_1$ and $z_2$, respectively, and $u(z_1)$ and $u(z_2)$ are the steady-state wind speeds at levels $z_1$ and $z_2$. The quantity $\Delta f_{0.5}$ is a nondimensional function of stability, where $\Delta f_{0.5}$ is that value for which the coherence (coh) is equal to 0.5, and values of this parameter for KSC are given in Table 2-22. The nondimensional quantity, $t$, should depend upon height and stability. However, it has only been possible to detect a dependence on height at KSC. Based upon analysis of turbulence data measured at the NASA 150-m Ground Wind Tower Facility at KSC, the values of $g$ in Table 2-23 are suggested for KSC. The quantity $\Delta f_{0.5}$, can be interpreted by constructing the coherence function, which is defined to be

$$\mathrm{coh}\,(w, z_1, z_2) = \frac{C^2 + Q^2}{S_1 S_2}\ . \tag{2.12}$$

TABLE 2-22. Values of $f_{0.5}$ for KSC.

| Turbulence Component | Light Wind Daytime Conditions | Strong Winds |
|---|---|---|
| Longitudinal | 0.04 | 0.036 |
| Lateral | 0.06 | 0.045 |

TABLE 2-23. Values Of $g$ For KSC.

| Turbulence Component | $(z_1+z_2)/2 \leq 100$ m | $(z_1+z_2)/2 > 100$ m |
|---|---|---|
| Longitudinal | 0.7 | 0.3 |
| Lateral | 1.4 | 0.5 |

Substituting equations (2.9) and (2.10) into equation (2.12) yields

$$\mathrm{coh}\,(w, z_1, z_2) = \exp\left(-0.693 \frac{\Delta f}{\Delta f_{0.5}}\right)\ . \tag{2.13}$$

2.2.6.4 Units. The spectral model of turbulence presented in subsections 2.2.6.2 and 2.2.6.3 is a dimensionless model. Accordingly, the user is free to select the system of units he desires, except that $w$ must have the units of cycles per unit time. Table 2-24 gives the appropriate metric and U.S. customary units for the various quantities in the model.

TABLE 2-24. Metric and U.S. Customary Units of Various Quantities In the Turbulence Model.

| Quantity | Metric Units | U.S. Customary Units |
|---|---|---|

| | | |
|---|---|---|
| $w$ | Hz | Hz |
| $S(w)$, $Q(w)$, $C(w)$ | $m^2\ s^{-2}$/Hz | $ft^2\ s^{-2}$/Hz |
| $f, f_m, \Delta f, \Delta f_{0.5}$ | Dimensionless | Dimensionless |
| $z, s_r, z_0$ | m | ft |
| $u, u_*$ | $ms^{-1}$ | ft $s^{-1}$ |
| $b$ | Dimensionless | Dimensionless |
| Coh | Dimensionless | Dimensionless |
| $g$ | Dimensionless | Dimensionless |
| $Y$ | Dimensionless | Dimensionless |

2.2.7 Ground Wind Gust Factors. The gust factor $G$ is defined to be

$$G = \frac{u}{\overline{u}} , \tag{2.14}$$

where

$u$ = maximum wind speed at height $z$ within an average period of length $t$ in time

$\overline{u}$ = mean wind speed associated with the average period $t$, given by

$$\overline{u} = \frac{1}{t}\int_0^t u_i\,(t)\,dt , \tag{2.15}$$

$u_i(t)$ = instantaneous wind speed at time $t$

$t$ = time reckoned from the beginning of the averaging period.

If $t = 0$, then $\overline{u} = u$ according to equation (2.15), and it follows from equation (2.14) that $G = 1.0$. As $t$ increases, $\overline{u}$ departs from $u$, and $\overline{u} \leq u$, and $G > 1.0$. Also, as $t$ increases, the probability of finding a maximum wind of a given magnitude increases. In other words, the maximum wind speed increases as $t$ increases. In the case of $\overline{u} \text{–>} 0$ and $u \geq 0$ ($\overline{u} = 0$ might correspond to windless free convection), $G \text{–>} \infty$. As $\overline{u}$ or $u$ increases, $G$ tends to decrease for fixed $t > 0$; while for very high wind speeds, $G$ tends to approach a constant value for given values of $z$ and $t$. Finally, as $z$ increases, $G$ decreases. Thus, the gust factor is a function of the averaging time, $t$, over which the mean wind speed is calculated, the height, $z$, and wind speed (mean or maximum).

2.2.7.1 Gust Factor as a Function of Peak Wind Speed ($u_{18.3}$) at Reference Height for KSC. Investigations (Ref. 2-8) of gust factor data have revealed that the vertical variation of the gust factor can be described with the following relationship:

$$G = 1 + \frac{1}{g_0}\left(\frac{18.3}{z}\right)^p , \tag{2.16}$$

where $z$ is the height in meters above natural grade. The parameter, $p$, a function of the 18.3-m peak wind speed in meters per second, is given by

$$p = 0.283 - 0.435\, e^{-0.2 u_{18.3}} \; . \qquad (2.17)$$

The parameter $g_0$ depends on the averaging time and the 18.3-m peak wind speed and is given by

$$g_0 = 0.085\left(ln \frac{t}{10}\right)^2 - 0.329\left(ln \frac{t}{10}\right) + 1.98 - 1.887\, e^{-0.2\, u_{18.3}} \; , \qquad (2.18)$$

where $t$ is given in minutes and $u_{18.3}$ in meters per second.

These relationships are valid for $u_{18.3} \geq 4$ m/s and $\tau \leq 10$ min. In the interval 10 min $\leq t \leq$ 60 min, $G$ is a slowly increasing monotonic function of $t$, and for all engineering purposes the 10-min gust factor ($t$ = 10 min) can be used as an estimate of the gust factors associated with averaging times greater than 10 min and less than 60 min (10 min $\leq t \leq$ 60 min).

The calculated mean gust factors for 10 min for values of $u_{18.3}$ in the interval 4.63 m/s $\leq u_{18.3} \leq \infty$ are presented in Table 2-25 in both the U.S. customary and metric units for $u_{18.3}$ and $z$. As an example, the gust factor profile for $\tau$ = 10 min and $u_{18.3}$ = 9.27 m/s (18 knots) is given in Table 2-26. Since the basic wind statistics are given in terms of hourly peak wind, use the $t$ = 10 min gust factors to convert the peak winds to mean winds by dividing by $G$. All gust factors in these sections are expected values for any particular set of values for $u$, $t$, and $z$.

2.2.7.2 Gust Factors for Other Locations. For design purposes, the gust factor value of 1.4 should be used over all heights of the ground wind profile at other test ranges. This gust factor should correspond to approximately a 10-min averaging period.

TABLE 2-25. 10-Minute Gust Factors for KSC.

| Reference Height 60-ft (18.3 m) Peak Wind knots (ms$^{-1}$) | Height Above Natural Grade in Feet (meters) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 33 (10.0) | 60 (18.3) | 100 (30.5) | 200 (61.0) | 300 (91.4) | 400 (121.9) | 500 (152.4) |
| 9.0 (4.63) | 1.868 | 1.812 | 1.767 | 1.710 | 1.679 | 1.658 | 1.642 |
| 10.0 (5.15) | 1.828 | 1.766 | 1.718 | 1.657 | 1.624 | 1.602 | 1.585 |
| 11.0 (5.66) | 1.795 | 1.729 | 1.678 | 1.614 | 1.580 | 1.556 | 1.539 |
| 12.0 (6.18) | 1.768 | 1.699 | 1.645 | 1.579 | 1.544 | 1.520 | 1.502 |
| 13.0 (6.69) | 1.746 | 1.674 | 1.618 | 1.552 | 1.514 | 1.489 | 1.471 |
| 14.0 (7.21) | 1.727 | 1.652 | 1.595 | 1.525 | 1.488 | 1.464 | 1.446 |
| 15.0 (7.72) | 1.712 | 1.634 | 1.576 | 1.505 | 1.467 | 1.442 | 1.424 |
| 16.0 (8.24) | 1.698 | 1.619 | 1.559 | 1.487 | 1.449 | 1.424 | 1.409 |
| 17.0 (8.75) | 1.686 | 1.606 | 1.545 | 1.472 | 1.424 | 1.409 | 1.390 |
| 18.0 (9.27) | 1.676 | 1.594 | 1.532 | 1.459 | 1.421 | 1.395 | 1.377 |
| 19.0 (9.78) | 1.668 | 1.584 | 1.522 | 1.447 | 1.409 | 1.384 | 1.365 |
| 20.0 (10.3) | 1.660 | 1.575 | 1.512 | 1.437 | 1.399 | 1.374 | 1.355 |
| 25.0 (12.9) | 1.634 | 1.545 | 1.480 | 1.403 | 1.365 | 1.339 | 1.321 |
| 30.0 (15.4) | 1.619 | 1.528 | 1.462 | 1.385 | 1.346 | 1.321 | 1.302 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ∞ (∞) | 1.599 | 1.505 | 1.437 | 1.359 | 1.320 | 1.295 | 1.277 |

TABLE 2-26. Gust Factor Profile For $t$ = 10 Min And $u_{18.3}$ = 9.27 M/S (18 Knots).

| Height | | Gust Factors |
|---|---|---|
| (ft) | (m) | (G) |
| 33 | 10.0 | 1.676 |
| 60 | 18.3 | 1.594 |
| 100 | 30.5 | 1.532 |
| 200 | 61.0 | 1.459 |
| 300 | 91.4 | 1.421 |
| 400 | 121.9 | 1.395 |
| 500 | 152.4 | 1.377 |

2.2.8 Ground Wind Shear. Wind shear near the surface, for design purposes, is a shear that acts upon an aerospace vehicle, freestanding on the pad, or at time of lift-off. For overturning moment calculations, the wind shear shall be computed by first subtracting the 10-min mean wind speed at the height corresponding to the base of the vehicle from the peak wind speed at the height corresponding to the top of the vehicle (see sections 2.3.5.5 for mean and peak wind profiles) and then dividing the difference by the height of the vehicle. The reader should consult references 2-9 through 2-17 for a detailed discussion of the statistical properties of wind shear near the ground for engineering applications.

2.2.9 Ground Wind Direction Characteristics. Figure 2-1 (subsection 2.2.5.1) shows a time trace of wind direction (section of a wind direction recording chart). This wind direction trace may be visualized as being composed of a mean wind direction plus fluctuations about the mean. An accurate measure of ambient wind direction near the ground is difficult to obtain sometimes because of the interference of the structure that supports the instrumentation and other obstacles in the vicinity of the measurement location (Ref. 2-18). This is particularly true for launch pads; therefore, care must be exercised in locating wind sensors in order to obtain representative measurements of the ambient wind direction.

General information, such as that which follows, is available and may be used to specify conditions for particular engineering studies. For instance, the variation of wind direction as a function of mean wind speed and height from analysis of NASA's 150-m Ground Winds Tower Facility data at KSC is discussed in reference 2-2. A graph is shown in reference 2-2 that gives values of the standard deviation of the wind direction $s_q$ as a function of height for a sampling time of approximately 5 min.

2.2.10 Design Winds for Facilities and Ground Support Equipment

2.2.10.1 Introduction. In this section, the important relationships between desired lifetime, $N$ (years); calculated risk, $U$ (%÷ 100); design return period, $T_D$ (years); and design wind, $W_D$ (m/s or knots) will be described for use in facilities design for several locations.

The desired lifetime $N$ is expressed in years, and preliminary estimates must be made as to how many years the proposed facility is to be used.

The calculated risk $U$ is a probability expressed either as a percentage or as a decimal fraction. Calculated risk, sometimes referred to as design risk, is a probability measure of the risk the designer is willing to accept that the facility will be destroyed by wind loading in less time than the desired lifetime.

The design return period $T_D$ is expressed in years and is a function of desired lifetime and calculated risk.

The design wind $W_D$ is a function of the desired lifetime and calculated risk and is derived from the design return period and a probability distribution function of yearly peak winds.

2.2.10.2 Development of Relationships. From the theory of repeated trial probability the following expression can be derived:

$$N = \frac{\ln(1-U)}{\ln\left(1-\frac{1}{T_D}\right)} . \quad (2.19)$$

Equation (2.19) gives the important relationships for the three variables, calculated risk, $U$ (%÷ 100); design return period, $T_D$ (years); and desired lifetime, $N$ (years). If estimates for any two variables are available, the third can be determined from this equation.

Design return period, $T_D$, calculated with equation (2.19), for various values of desired lifetime, $N$, and design risk are given in Table 2-27. The table presents the exact and adopted values for design return period versus desired lifetime for various design risks. The adopted values for $T_D$ are in some cases greatly oversized to facilitate a convenient use of the tabulated probabilities for distributions of yearly peak winds.

TABLE 2-27. Exact (Ex) And Adopted Values For Design Return Period ($T_D$, Years) Versus Desired Lifetime ($N$, Years) For Various Design Risks ($U$).

| $N$ (years) | Design Return Period (years) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $U$ = 0.5 (50%) | | $U$ = 0.2 (20%) | | $U$ = 0.1 (10%) | | $U$ = 0.05(5%) | | $U$ = 0.01 (1%) | |
| | Ex | Adopt | Ex | Adopt | Ex | Adopt | Ex | Adopt | Ex | Adopt |
| 1 | 2 | 2 | 15 | 5 | 10 | 10 | 20 | 20 | 100 | 100 |
| 10 | 15 | 15 | 45 | 50 | 95 | 100 | 196 | 200 | 996 | 1,000 |
| 20 | 29 | 30 | 90 | 100 | 190 | 200 | 390 | 400 | 1,991 | 2,000 |
| 25 | 37 | 40 | 113 | 125 | 238 | 250 | 488 | 500 | | |
| 30 | 44 | 50 | 135 | 150 | 285 | 300 | 585 | 600 | | |
| 50 | 73 | 100 | 225 | 250 | 475 | 500 | 975 | 1,000 | | |
| 100 | 145 | 150 | 449 | 500 | 950 | 1,000 | 1,950 | 2,000 | | |

2.2.10.3 Design Winds for Facilities. To obtain the design wind, the wind speed corresponding to the design return period must be determined. Since the design return period is a function of risk, either of two procedures can be used to determine the design wind: One is through a graphical or numerical interpolation procedure; the second is based on an analytical function. A knowledge of the distribution of yearly peak winds is required for both procedures. For the greatest statistical efficiency in arriving at the probability that the peak winds will be less than or equal to some specified value of yearly peak winds, an appropriate probability distribution function must be selected, and the parameters for the function estimated from the sample of yearly peak winds. The Gumbel distribution (Ref. 2.56) is an excellent fit for the yearly peak ground wind speed at the 10-m level for KSC. The distribution of yearly peak wind speed (10-m level), as obtained by the Gumbel distribution, is tabulated for various percentiles together with the corresponding return periods in Table 2-28. The values for the parameters $\alpha$ and $m$ for this distribution are also given in this table.

The design wind speed can now be determined by choosing a desired lifetime, design risk, by taking the design return period from Table 2-27 and looking up the wind speed corresponding to the return periods in Table 2-28. For combinations not tabulated in Tables 2-27 and 2-28, the design return period can be interpolated.

2.2.10.4 Procedure to Determine Design Winds for Facilities. The design wind, $W_D$, as a function of desired lifetime, $N$, and calculated risk, $U$, for the Gumbel distribution of peak winds at the 10-m reference level, can be derived as

$$W_D = \frac{1}{a}\left[-ln[-ln(1-U)] + ln N\right] + m \ , \qquad (2.20)$$

where $a$ and $m$ are estimated from the sample of yearly peak wind.

Taking the values for $a^{-1}$ = 5.59 m/s (10.87 knots) and for $m$ = 23.4 m/s (45.49 knots) from Table 2-28 and evaluating equation (2.20) for selected values of $N$ and $U$ yields the data in Table 2-29.

Design wind speed versus desired lifetime is plotted in Figure 2-7 where the slopes of the lines are equal.

TABLE 2-28. Gumbel Distribution For Yearly Peak Wind Speed, 10-m Reference Level, Including Hurricane Winds, KSC.

| Return Period (years) | Probability | y | m/s | knots |
|---|---|---|---|---|
| 2 | 0.50 | 0.36651 | 25.45 | 49.47 |
| 5 | 0.80 | 1.49994 | 31.79 | 61.79 |
| 10 | 0.90 | 2.25037 | 35.98 | 69.95 |
| 15 | 0.933 | 2.66859 | 38.33 | 74.50 |
| 20 | 0.95 | 2.97020 | 40.01 | 77.77 |
| 30 | 0.967 | 3.39452 | 42.38 | 82.39 |
| 45 | 0.978 | 3.80561 | 44.68 | 86.86 |
| 50 | 0.98 | 3.90191 | 45.22 | 87.90 |
| 90 | 0.9889 | 4.49523 | 48.54 | 94.35 |
| 100 | 0.99 | 4.60015 | 49.12 | 95.49 |
| 150 | 0.9933 | 5.00229 | 51.37 | 99.86 |
| 200 | 0.995 | 5.29581 | 53.01 | 103.05 |
| 250 | 0.996 | 5.51946 | 54.26 | 105.48 |
| 300 | 0.9967 | 5.71218 | 55.34 | 107.58 |
| 400 | 0.9975 | 5.99021 | 56.90 | 110.60 |
| 500 | 0.9980 | 6.21361 | 58.14 | 113.02 |
| 600 | 0.9983 | 6.37628 | 58.75 | 114.20 |
| 1,000 | 0.9990 | 6.90726 | 62.02 | 120.56 |
| 10,000 | 0.9999 | 9.21029 | 74.90 | 145.60 |

$a^{-1}$ = 5.5917 m/s (10.87 knots) $m$ = 23.4 m/s (45.49 knots)
$F = \exp(-\exp(-y))$ , where $y = a(x-m)$
$F$ is the probability distribution function of the reduced variate, $y$.

TABLE 2-29. Facility Design Wind, $W_{D\,10}$, With Respect To The 10-M Reference Level Peak Wind Speed For Various Lifetimes (*N*), KSC.*

| Design Risk $U$ | $1-U$ | $-\ln(-\ln(1-U))$ | Design Wind ($W_{D10}$) for Various Lifetimes ($N$)* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $N = 1$ | | $N = 10$ | | $N = 30$ | | $N = 100$ | |
| | | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 0.63212 | 0.36788 | 0 | 23.40 | 45.49 | 36.28 | 70.52 | 42.42 | 82.46 | 49.15 | 95.55 |
| 0.50 | 0.50 | 0.37 | 25.45 | 49.47 | 38.33 | 74.50 | 44.47 | 86.44 | 51.20 | 99.53 |
| 0.4296 | 0.5704 | 0.58 | 26.62 | 51.76 | 39.50 | 76.79 | 45.65 | 88.73 | 52.38 | 101.82 |
| 0.40 | 0.60 | 0.67 | 27.16 | 52.79 | 40.03 | 77.82 | 46.18 | 89.76 | 52.92 | 102.85 |
| 0.30 | 0.70 | 1.03 | 29.17 | 56.70 | 42.04 | 81.72 | 48.19 | 93.67 | 54.92 | 106.75 |
| 0.20 | 0.80 | 1.50 | 31.79 | 61.79 | 44.66 | 86.82 | 50.81 | 98.76 | 57.54 | 111.85 |
| 0.10 | 0.90 | 2.25 | 35.99 | 69.95 | 48.86 | 94.98 | 55.00 | 106.92 | 61.74 | 120.01 |
| 0.05 | 0.95 | 2.97 | 40.01 | 77.77 | 52.88 | 102.80 | 59.03 | 114.74 | 65.76 | 127.83 |
| 0.01 | 0.99 | 4.60 | 49.12 | 95.49 | 62.00 | 120.52 | 68.14 | 132.46 | 74.88 | 145.55 |

*Values of *N* are given in years.

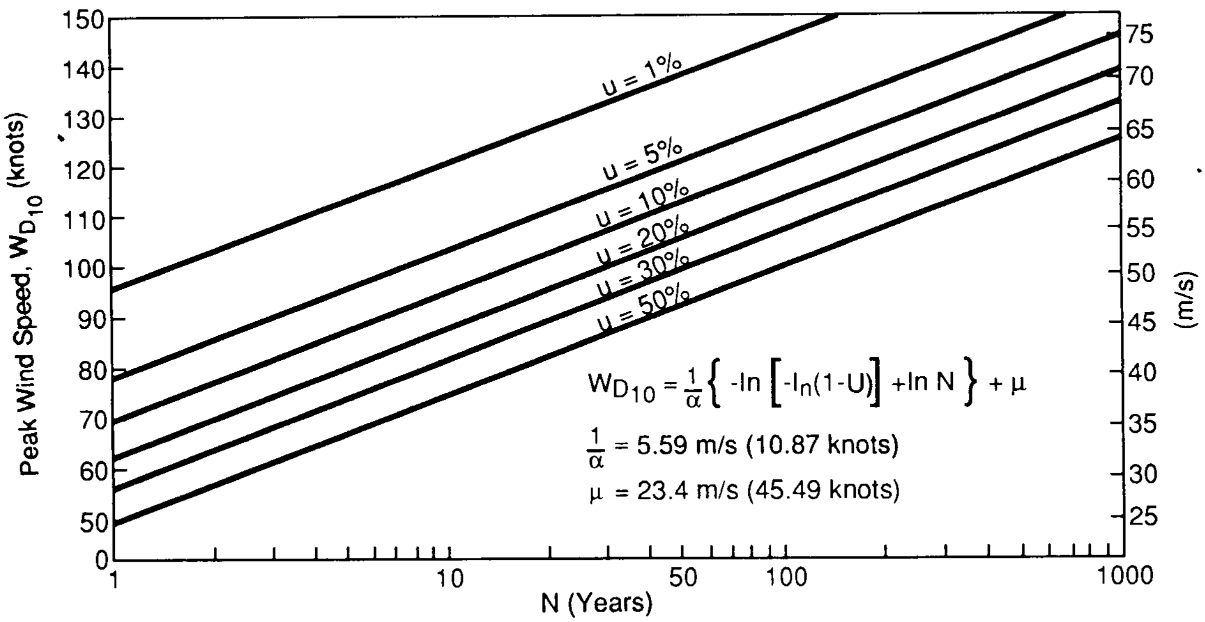



FIGURE 2-7. Facility Design Wind, $W_{D\,10}$, With Respect to the 10-M Reference Level Peak Wind Speed for Various Lifetimes (*N*), KSC.

2.2.10.5 Wind Load Calculations. The design wind for a structure cannot be determined solely by wind statistics at a particular height. The design engineer is most interested in designing a structure which satisfies the user's requirements for utility, which will have a small risk of failure within the desired lifetime of the structure, and which can carry a sufficiently large wind load and be constructed at a sufficiently low cost. The total wind loading on a structure is composed of two interrelated components, steady-state drag wind loads and dynamic wind loads (time-dependent drag loads, vortex shedding forces, etc.). The time required for a structure to respond to the drag wind loads dictates the averaging time for the design wind profile. In general, the structure response time depends upon the shape of the structure. The natural frequency of the structure and its components are important in estimating the dynamic wind load. It is conceivable that a structure could be designed to withstand very high wind speeds without structural failure and still oscillate in moderate wind speeds. If such a structure, for example, is to be used to support a precision tracking radar, then there may be little danger of overloading the structure by high winds; but the structure might be useless for its intended purpose if it were to oscillate in a moderate wind. Also, a building may have panels or small members that could respond to dynamic loading in such a way that long-term vibrations could cause failure, without any structural failure of the main supporting members. Since dynamic wind loading requires an intricate knowledge of the particular facility and its components, no attempt is made here to state generalized design criteria for dynamic wind loading. The emphasis in this section is upon winds for estimating drag wind loads in establishing design wind criteria for structures. Reference is made to subsection 2.2.5.5 and 2.2.6 for information appropriate to dynamic wind loads.

2.2.10.6 Wind Profile Construction. Given the peak wind at the 10-m level, the peak wind profile can be constructed with the peak wind profile law from subsection 2.2.5.5. Steady-state wind profiles can be obtained by using appropriate gust factors which are discussed in subsection 2.2.7.

To illustrate the procedures and operations in deriving the wind profile and the application of the gust factor, three examples are worked out for KSC. Peak wind speeds at the 10-m level of 36, 49, and 62 m/s (70, 95, and 120 knots) have been selected for these examples. These three wind speeds were selected because they correspond to a return period of 10, 100, and 1,000 years for a peak wind at the 10-m level at KSC. Table 2-30 contains the risks of exceeding these peak winds for various values of desired lifetime. Table 2-31 gives the peak design wind profiles corresponding to the desired lifetimes and calculated risks presented in Table 2-30. These profiles were calculated with equation (2.22).

TABLE 2-30. Calculated Risk ($U$) Versus Desired Lifetime ($N$, Years) for Assigned Design Winds Related to Peak Winds at the 10-m Reference Level, KSC.

| $N$ (years) | $W_{D10}$ = 36 m/s (70 knots) $T_D$ = 10 years $U$% | $W_{D10}$ = 49 m/s (95 knots) $T_D$ = 100 years $U$% | $W_{D10}$ = 62 m/s (120 knots) $T_D$ = 1,000 years $U$% |
|---|---|---|---|
| 1 | 10 | 1.0 | 0.1 |
| 10 | 65 | 10 | 1 |
| 20 | 88 | 18 | 2 |
| 25 | 93 | 22 | 2.5 |
| 30 | 95.8 | 26 | 3 |
| 50 | 99.5 | 39.5 | 5 |
| 100 | 99.997 | 63.397 | 10 |
| $T_D$ = Design return period | | | |

TABLE 2-31. Design Peak Wind Profiles For Design Wind Relative To The 10-M Reference Level, KSC.

| Height | | $W_{D10}$ = 36 m/s (70 knots) | | $W_{D10}$ = 49 m/s (95 knots) | | $W_{D10}$ = 62 m/s (120 knots) | |
|---|---|---|---|---|---|---|---|
| (ft) | (m) | (knots) | ($ms^{-1}$) | (knots) | ($ms^{-1}$) | (knots) | ($ms^{-1}$) |
| 33 | 10.0 | 70.0 | 36.0 | 95.0 | 48.9 | 120.0 | 61.8 |
| 60 | 18.3 | 74.5 | 38.4 | 99.9 | 51.4 | 125.2 | 64.5 |
| 100 | 30.5 | 78.6 | 40.0 | 104.2 | 53.7 | 129.8 | 66.8 |
| 200 | 61.0 | 84.4 | 43.4 | 110.4 | 56.8 | 136.2 | 70.1 |
| 300 | 91.4 | 88.0 | 45.3 | 114.2 | 58.8 | 140.2 | 72.2 |
| 400 | 121.9 | 90.7 | 46.7 | 117.0 | 60.2 | 143.0 | 73.6 |
| 500 | 152.4 | 92.8 | 47.8 | 119.1 | 61.3 | 145.3 | 74.8 |

TABLE 2-32. Gust Factors For Various Averaging Times ($t$) For Peak Winds > 15 M/S (29 Knots) At The 10-m Reference Level Versus Height, KSC.

| Height | | Various Averaging Times ($t$, min) | | | | |
|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0.5 | $t$ = 1 | $t$ = 2 | $t$ = 5 | $t$ = 10 |
| 33 | 10.0 | 1.318 | 1.372 | 1.528 | 1.599 | 1.599 |
| 60 | 18.3 | 1.268 | 1.314 | 1.445 | 1.505 | 1.505 |
| 100 | 30.5 | 1.232 | 1.271 | 1.385 | 1.437 | 1.437 |
| 200 | 61.0 | 1.191 | 1.223 | 1.316 | 1.359 | 1.359 |
| 300 | 91.4 | 1.170 | 1.199 | 1.282 | 1.320 | 1.320 |
| 400 | 121.9 | 1.157 | 1.183 | 1.260 | 1.295 | 1.295 |
| 500 | 152.4 | 1.147 | 1.172 | 1.244 | 1.277 | 1.277 |

2.2.10.7 Use of Gust Factors Versus Height. In estimating the drag load on a particular structure, it may be determined that wind force of a given magnitude must act on the structure for some period (for example, 1 min) to produce a critical drag load. To obtain the wind profile corresponding to a time-averaged wind, the peak wind profile values are divided by the required gust factors. The gust factors for winds greater than 15 m/s (29 knots) versus height given in Table 2-32 are taken from section 2.2.7. This operation may seem strange to someone who is accustomed to multiplying the given wind by a gust factor in establishing the design wind. This is because most literature on this subject gives the reference wind as averaged over some time increment (for example, 1, 2, or 5 min) or in terms of the "fastest mile" of wind that has a variable averaging time depending upon the wind speed. The design wind profiles for the three examples, peak winds of 36, 49, and 62 m/s (70, 95, and 120 knots) at the 10-m level for various averaging times $t$, given in minutes, are illustrated in Tables 2-33, 2-34, and 2-35. Following the procedures presented herein, the design engineer can objectively derive several important design parameters that can be used in designing a facility that will (1) meet the requirements for utility and desired lifetime, (2) withstand a sufficiently large wind loading with a known calculated risk of failure due to wind loads, and (3) allow him to proceed with trade-off studies between the design parameters and to estimate the cost of building the structure to best meet these design objectives.

TABLE 2-33. Design Wind Profiles For Various Averaging Times ($t$) For Peak Design Wind Of 36.0 M/S (70.0 Knots) Relative To The 10-m Reference Level, KSC.

| Height | | Design Wind Profiles for Various Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 36.0 | 70.0 | 27.3 | 53.1 | 26.2 | 51.0 | 25.1 | 48.8 | 23.6 | 45.8 | 22.5 | 43.8 |
| 60 | 18.3 | 38.3 | 74.5 | 30.2 | 58.8 | 29.2 | 56.7 | 28.0 | 54.5 | 26.5 | 51.6 | 25.5 | 49.5 |
| 100 | 30.5 | 40.4 | 78.6 | 32.8 | 63.8 | 31.8 | 61.8 | 30.7 | 59.7 | 29.2 | 56.8 | 28.1 | 54.7 |
| 200 | 61.0 | 43.4 | 84.4 | 36.5 | 70.9 | 35.5 | 69.0 | 34.4 | 66.9 | 33.0 | 64.1 | 31.9 | 62.1 |
| 300 | 91.4 | 45.3 | 88.0 | 38.7 | 75.2 | 37.8 | 73.4 | 36.7 | 71.4 | 35.3 | 68.6 | 34.3 | 66.7 |
| 400 | 121.9 | 46.7 | 90.7 | 40.3 | 78.4 | 39.5 | 76.7 | 38.4 | 74.7 | 37.0 | 72.0 | 36.0 | 70.0 |
| 500 | 152.4 | 47.7 | 92.8 | 41.6 | 80.9 | 40.7 | 79.2 | 39.8 | 77.3 | 38.4 | 74.6 | 37.4 | 72.7 |

TABLE 2-34. Design Wind Profiles for Various Averaging Times ($t$) for Peak Design Wind of 49.0 M/S (95 Knots) Relative to the 10-m Reference Level, KSC.

| Height | | Design Wind Profiles for Various Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 48.9 | 95.0 | 37.1 | 72.1 | 35.6 | 69.2 | 34.1 | 66.2 | 32.0 | 62.2 | 30.6 | 59.4 |
| 60 | 18.3 | 51.4 | 99.9 | 40.5 | 78.8 | 39.1 | 76.0 | 37.6 | 73.1 | 35.5 | 69.1 | 34.2 | 66.4 |
| 100 | 30.5 | 53.6 | 104.2 | 43.5 | 84.6 | 42.2 | 82.0 | 40.7 | 79.1 | 38.7 | 75.2 | 37.3 | 72.5 |
| 200 | 61.0 | 56.8 | 110.4 | 47.7 | 92.7 | 46.5 | 90.3 | 45.0 | 87.5 | 43.2 | 83.9 | 41.8 | 81.2 |
| 300 | 91.4 | 58.7 | 114.2 | 50.2 | 97.6 | 49.0 | 95.2 | 47.7 | 92.7 | 45.8 | 89.1 | 44.5 | 86.5 |
| 400 | 121.9 | 60.2 | 117.0 | 52.0 | 101.1 | 50.9 | 98.9 | 49.6 | 96.4 | 47.8 | 92.9 | 46.5 | 90.3 |
| 500 | 152.4 | 61.3 | 119.1 | 53.4 | 103.8 | 52.3 | 101.6 | 51.0 | 99.2 | 49.2 | 95.7 | 48.0 | 93.3 |

TABLE 2-35. Design Wind Profiles For Various Averaging Times ($t$) For Peak Design Wind Of 62.0 M/S (120 Knots) Relative To The 10-m Reference Level, KSC

| Height | | Design Wind Profiles for Various Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 61.7 | 120.0 | 46.8 | 91.0 | 45.0 | 87.5 | 43.0 | 83.6 | 40.4 | 78.5 | 38.6 | 75.0 |
| 60 | 18.3 | 64.4 | 125.2 | 50.8 | 98.7 | 49.0 | 95.3 | 47.2 | 91.7 | 44.6 | 86.6 | 42.8 | 83.2 |
| 100 | 30.5 | 66.8 | 129.8 | 54.2 | 105.4 | 52.5 | 102.1 | 50.7 | 98.6 | 48.2 | 93.7 | 46.5 | 90.3 |
| 200 | 61.0 | 70.1 | 136.2 | 58.9 | 114.4 | 57.3 | 111.4 | 55.6 | 108.0 | 53.2 | 103.5 | 51.5 | 100.2 |
| 300 | 91.4 | 72.1 | 140.2 | 61.6 | 119.8 | 60.1 | 116.9 | 58.5 | 113.8 | 56.3 | 109.4 | 54.6 | 106.2 |
| 400 | 121.9 | 73.6 | 143.0 | 63.6 | 123.6 | 62.2 | 120.9 | 60.6 | 117.8 | 58.4 | 113.5 | 56.8 | 110.4 |
| 500 | 152.4 | 74.7 | 145.3 | 65.2 | 126.7 | 63.8 | 124.0 | 62.2 | 121.0 | 60.1 | 116.8 | 58.5 | 113.8 |

2.2.10.8 Recommended Design Risk Versus Desired Lifetime. Unfortunately, there is not a clear-cut precedent from building codes to follow in recommending design risk for a given desired lifetime of a structure. Conceivably, a value analysis in terms of original investment cost, replacement cost, safety of property and human life, loss of national prestige, and many other factors should be made to give a measure of the consequences of the loss of a particular structure in arriving at a decision as to what risk management is willing to accept for the loss within the desired lifetime of the structure. If the structure is an isolated shed, then obviously its loss is not as great as a structure that would house many people or a structure that is critical to the mission of a large organization; nor is it as potentially unsafe as the loss of a nuclear power plant or storage facility for explosives or highly radioactive materials. To give a starting point for design studies aimed at meeting the design objectives, it is recommended that a design risk of 10 percent for the desired lifetime be used in determining the wind loading on structures that have a high replacement cost. Should the loss of the structure be extremely hazardous to life or property, or critical to the mission of a large organization, then a design risk of 5 percent or less for the desired lifetime is recommended. These are subjective recommendations involving arbitrary assumptions about the design objectives. Note that the longer the desired lifetime, the greater the design risk is for a given wind speed (or wind loading). Therefore, realistic appraisals should be made for desired lifetimes.

2.2.10.9 Design Winds for Facilities at VAFB, White Sands Missile Range, Edwards AFB, and Stennis Space Center.

2.2.10.9.1 Wind Statistics. The basic wind statistics for these four locations are taken from reference 2-19, which presents isotach maps for the United States for the 50-, 98-, and 99-percentile values for the yearly maximum "fastest mile" of wind at the ~10-m (30-ft) reference height above natural grade. By definition, the fastest mile is the fastest wind speed in miles per hour of any mile of wind flow past an anemometer during a specified period (usually taken as the 24-h observational day), and the largest of these in a year for the period of record constitutes the statistical sample of yearly fastest mile. From this definition, it is noted that the fastest mile as a measure of wind speed has a variable averaging time; for example, if the wind speed is 60 miles per hour (mi/h), the averaging time for the fastest mile of wind is 1 min. For a wind speed of 120 mi/h, the averaging time for the fastest mile of wind is 0.5 min. Thom (Ref. 2-19) reports that the Frechet probability distribution function fits his samples of fastest mile very well. The Frechet probability distribution function is given as

$$F(x) = e^{-\left(\frac{x}{b}\right)^{-g}} , \qquad (2.21)$$

where the two parameters $b$ and $g$ are estimated from the sample by the maximum likelihood method. From Thom's maps of the 50, 98, and 99 percentiles of fastest mile of wind for yearly extremals, we have estimated (interpolated) for these percentiles for the four locations and calculated the values for the parameters $b$ and $g$ for the Frechet distribution function and computed several additional percentiles, as shown in Table 2-36. To have units consistent with the other sections of this document, the percentiles and the parameters $b$ and $g$ have been converted from miles per hour to knots and m/s. Thus Table 2-36 gives the Frechet distribution for the fastest mile of winds at the ~10-m (30-ft) level for the four locations with the units in knots and m/s.

The discussion in section 2.2.10.2, devoted to desired lifetime, calculated risk, and design wind relationships with respect to the wind statistics at a particular height (10-m level) is applicable here, except that the reference statistics are with respect to the fastest mile converted to knots and m/s. (Also see reference 2-20.)

2.2.10.9.2 Conversion of the Fastest Mile to Peak Winds. The Frechet distributions for the fastest mile were obtained from Thom's analysis for KSC. From these two distributions (the Frechet for the peak winds as well as for the fastest mile), the ratio of the percentiles of the fastest mile to the peak winds were taken. This ratio varied from 1.12 to 1.09 over the range of probabilities from 30 to 99 percent. Thus, we adopted 1.10 as a factor to multiply the statistics of the fastest mile of wind to obtain peak (instantaneous) wind statistics. This procedure is based on the evidence of only one station. A gust factor of 1.10 is often applied to the fastest mile statistics in facility design work to account for gust loads.

TABLE 2-36. Frechet Distribution of Fastest Mile Wind at the 10-M Height of Yearly Extremes for the Indicated Locations.

| $P$ Probability | $T_D$ Return Period (years) | Fastest Mile Wind | | | | | |
|---|---|---|---|---|---|---|---|
| | | Stennis Space Center | | Vandenberg AFB | | Edwards AFB | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 0.50 | 2 | 22.1 | 42.9 | 18.0 | 34.9 | 11.3 | 22.0 |
| 0.80 | 5 | 26.6 | 51.8 | 21.6 | 42.0 | 15.0 | 29.1 |
| 0.90 | 10 | 30.1 | 58.6 | 24.4 | 47.4 | 18.1 | 35.2 |
| 0.95 | 20 | 33.9 | 65.9 | 27.4 | 53.3 | 21.6 | 42.0 |
| 0.98 | 50 | 39.6 | 76.9 | 31.8 | 61.9 | 27.3 | 53.0 |
| 0.99 | 100 | 44.4 | 86.4 | 35.7 | 69.4 | 32.4 | 63.1 |
| 0.9933 | 150 | 47.4 | 92.2 | 38.0 | 73.9 | 35.1 | 68.3 |
| 0.995 | 200 | 49.7 | 96.7 | 39.9 | 77.6 | 38.6 | 75.0 |
| 0.996 | 250 | 51.6 | 100.4 | 41.4 | 80.4 | 40.8 | 79.3 |
| 0.99667 | 300 | 53.2 | 103.5 | 42.6 | 82.9 | 42.7 | 83.1 |
| 0.9975 | 400 | 55.8 | 108.4 | 44.6 | 86.7 | 45.8 | 89.1 |
| 0.998 | 500 | 57.9 | 112.5 | 46.2 | 89.9 | 48.5 | 94.2 |
| 0.99833 | 600 | 59.4 | 115.5 | 47.5 | 92.3 | 50.5 | 98.1 |
| 0.99875 | 800 | 62.6 | 121.6 | 50.3 | 97.7 | 54.0 | 105.0 |
| 0.999 | 1,000 | 64.9 | 126.1 | 51.8 | 100.6 | 57.6 | 111.9 |
| $g$ | Unitless | 6.08075 | | 6.19591 | | 4.02093 | |
| $1/g$ | Unitless | 0.16445 | | 0.16140 | | 0.24870 | |
| $\ln b$ | Unitless | 3.70093 | | 3.49620 | | 2.99989 | |
| $b$ | m/s (knots) | 20.829 (40.488) | | 16.968 (32.983) | | 10.322 (20.065) | |

2.2.10.9.3 The Peak Wind Profile. The peak wind profile law adopted for the four locations for peak winds at the 10-m level greater than 22.6 m/s (44 knots) is

$$u = u_{10} \left(\frac{z}{10}\right)^{1/7} , \tag{2.22}$$

where $u_{10}$ is the peak wind at the 10-m height and $u$ is the peak wind at height $z$ in meters.

2.2.10.9.4 The Mean Wind Profile. To obtain the mean wind profile for various averaging times, the gust factors (Table 2-32) are applied to the peak wind profile as determined by equation (2.22).

2.2.10.9.5 Design Wind Profiles for Station Locations. The design peak wind profiles for the peak winds in Table 2-37 are obtained from the peak wind power law given by equation (2.22), and the mean wind profiles for various averaging times are obtained by dividing by the gust factors for the various averaging times. (The gust factors versus height and averaging times are presented in Table 2-32.) The resulting selected design wind profiles for design return periods of 10, 100, and 1,000 years for the four locations are given in Tables 2-38 through 2-46, in which values of $t$ are given in minutes. The design risk versus desired lifetime for the design return periods of 10, 100, and 1,000 years is presented in Table 2-30.

TABLE 2-37. Peak Winds (Fastest Mile Values Times 1.10) for the 10-m Reference Level for 10-, 100-, and 1,000-Year Return Periods.

| $T_D$ (years) | Peak Winds ($U_{10}$) | | | | | |
|---|---|---|---|---|---|---|
| | Stennis Space Center | | Vandenberg AFB | | Edwards AFB | |
| | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 10 | 33.2 | 64.5 | 26.8 | 52.1 | 19.9 | 38.7 |
| 100 | 48.9 | 95.0 | 39.3 | 76.3 | 35.7 | 69.4 |
| 1,000 | 71.4 | 138.7 | 56.9 | 110.7 | 63.4 | 123.2 |

TABLE 2-38. Facilities Design Wind As A Function Of Averaging Time ($t$) For A Peak Wind Of 33.2 M/S(64.5 Knots) (10-Year Return Period) For Stennis Space Center.

| Height | | Facilities Design Wind as a Function of Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 (peak) | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 33.2 | 64.5 | 25.2 | 48.9 | 24.2 | 47.0 | 23.1 | 44.9 | 21.7 | 42.2 | 20.7 | 40.3 |
| 60 | 18.3 | 36.2 | 70.3 | 28.5 | 55.4 | 27.5 | 53.5 | 26.5 | 51.5 | 25.1 | 48.7 | 24.0 | 46.7 |
| 100 | 30.5 | 38.9 | 75.6 | 31.6 | 61.4 | 30.6 | 59.5 | 29.5 | 57.4 | 28.1 | 54.6 | 27.1 | 52.6 |
| 200 | 61.0 | 43.0 | 83.5 | 36.1 | 70.1 | 35.1 | 68.3 | 34.1 | 66.2 | 32.6 | 63.4 | 31.6 | 61.4 |
| 300 | 91.4 | 45.5 | 88.5 | 38.9 | 75.6 | 38.0 | 73.8 | 36.9 | 71.8 | 35.5 | 69.0 | 34.5 | 67.0 |
| 400 | 121.9 | 47.4 | 92.2 | 41.0 | 79.7 | 40.1 | 77.9 | 39.0 | 75.9 | 37.7 | 73.2 | 36.6 | 71.2 |
| 500 | 152.4 | 48.5 | 94.3 | 42.3 | 82.2 | 41.4 | 80.5 | 40.4 | 78.5 | 39.0 | 75.8 | 38.0 | 73.8 |

TABLE 2-39. Facilities Design Wind As A Function of Averaging Time ($t$) for a Peak Wind of 48.9 m/s (95.0 Knots) (100-Year Return Period) for Stennis Space Center

| Height | | Facilities Design Wind as a Function of Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 (peak) | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 48.9 | 95.0 | 37.1 | 72.1 | 35.6 | 69.2 | 34.1 | 66.2 | 32.0 | 62.2 | 30.6 | 59.4 |
| 60 | 18.3 | 53.3 | 103.6 | 42.0 | 81.7 | 40.5 | 78.8 | 39.0 | 75.8 | 36.9 | 71.7 | 35.4 | 68.8 |
| 100 | 30.5 | 57.3 | 111.4 | 46.5 | 90.4 | 45.1 | 87.6 | 43.5 | 84.6 | 41.4 | 80.4 | 40.8 | 79.3 |
| 200 | 61.0 | 63.3 | 123.0 | 53.1 | 103.3 | 51.8 | 100.6 | 50.2 | 97.5 | 48.1 | 93.5 | 46.6 | 90.5 |
| 300 | 91.4 | 67.0 | 130.3 | 57.3 | 111.4 | 55.9 | 108.7 | 54.4 | 105.8 | 52.3 | 101.6 | 50.8 | 98.7 |
| 400 | 121.9 | 69.9 | 135.8 | 60.4 | 117.4 | 59.1 | 114.8 | 57.6 | 111.9 | 55.5 | 107.8 | 54.0 | 104.9 |
| 500 | 152.4 | 71.4 | 138.8 | 62.2 | 121.0 | 60.9 | 118.4 | 59.5 | 115.6 | 57.4 | 111.6 | 55.9 | 108.7 |

TABLE 2-40. Facilities Design Wind As A Function Of Averaging Time ($t$) For A Peak Wind Of 71.4 m/s (138.7 Knots) (1,000-Year Return Period) For Stennis Space Center.

| Height | | Facilities Design Wind as a Function of Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 (peak) | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 71.4 | 138.7 | 54.1 | 105.2 | 52.0 | 101.1 | 49.7 | 96.7 | 46.7 | 90.8 | 44.6 | 86.7 |
| 60 | 18.3 | 77.8 | 151.2 | 61.3 | 119.2 | 59.2 | 115.1 | 56.9 | 110.7 | 53.8 | 104.6 | 51.7 | 100.5 |
| 100 | 30.5 | 83.7 | 162.7 | 68.0 | 132.1 | 65.8 | 128.0 | 63.5 | 123.5 | 60.4 | 117.5 | 58.2 | 113.2 |
| 200 | 61.0 | 92.4 | 179.6 | 77.6 | 150.8 | 75.6 | 146.9 | 73.3 | 142.4 | 70.2 | 136.5 | 68.0 | 132.2 |
| 300 | 91.4 | 97.9 | 190.3 | 83.6 | 162.6 | 81.6 | 158.7 | 79.5 | 154.5 | 76.3 | 148.4 | 74.2 | 144.2 |
| 400 | 121.9 | 102.0 | 198.2 | 88.1 | 171.3 | 86.2 | 167.5 | 84.0 | 163.3 | 80.9 | 157.3 | 78.8 | 153.1 |
| 500 | 152.4 | 104.3 | 202.7 | 90.9 | 176.7 | 89.0 | 173.0 | 86.8 | 168.8 | 83.8 | 162.9 | 81.6 | 158.7 |

TABLE 2-41. Facilities Design Wind As A Function of Averaging Time ($t$) For A Peak Wind Of 26.8 m/s (52.1 Knots) (10-Year Return Period) For VAFB And White Sands Missile Range.

| Height | | Facilities Design Wind as a Function of Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 (peak) | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 26.8 | 52.1 | 20.3 | 39.5 | 19.5 | 38.0 | 18.7 | 36.3 | 17.5 | 34.1 | 16.8 | 32.6 |
| 60 | 18.3 | 29.2 | 56.8 | 23.0 | 44.8 | 22.2 | 43.2 | 21.4 | 41.6 | 20.2 | 39.3 | 19.4 | 37.7 |
| 100 | 30.5 | 31.4 | 61.1 | 25.5 | 49.6 | 24.7 | 48.1 | 23.9 | 46.4 | 22.7 | 44.1 | 21.9 | 42.5 |
| 200 | 61.0 | 34.7 | 67.5 | 29.2 | 56.7 | 28.4 | 55.2 | 27.5 | 53.5 | 26.4 | 51.3 | 25.6 | 49.7 |
| 300 | 91.4 | 36.8 | 71.5 | 31.4 | 61.1 | 30.7 | 59.6 | 29.8 | 58.0 | 28.7 | 55.8 | 27.9 | 54.2 |
| 400 | 121.9 | 38.3 | 74.5 | 33.1 | 64.4 | 32.4 | 63.0 | 31.6 | 61.4 | 30.4 | 59.1 | 29.6 | 57.5 |
| 500 | 152.4 | 39.1 | 76.1 | 34.1 | 66.3 | 33.4 | 64.9 | 32.6 | 63.3 | 31.5 | 61.2 | 30.7 | 59.6 |

TABLE 2-42. Facilities Design Wind As A Function of Averaging Time ($t$) For a Peak Wind of 39.3 m/s (76.3 Knots) (100-Year Return Period) For VAFB And White Sands Missile Range.

| Height | | Facilities Design Wind as a Function of Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 (peak) | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 39.3 | 76.3 | 29.8 | 57.9 | 28.6 | 55.6 | 27.4 | 53.2 | 25.7 | 49.9 | 24.5 | 47.7 |
| 60 | 18.3 | 42.8 | 83.2 | 33.7 | 65.6 | 32.6 | 63.3 | 31.3 | 60.9 | 29.6 | 57.6 | 28.4 | 55.3 |
| 100 | 30.5 | 46.0 | 89.5 | 37.3 | 72.6 | 36.2 | 70.4 | 35.0 | 68.0 | 33.2 | 64.6 | 32.0 | 62.3 |
| 200 | 61.0 | 50.8 | 98.8 | 42.7 | 83.0 | 41.6 | 80.8 | 40.3 | 78.4 | 38.6 | 75.1 | 37.4 | 72.7 |
| 300 | 91.4 | 53.9 | 104.7 | 46.0 | 89.5 | 44.9 | 87.3 | 43.7 | 85.0 | 42.0 | 81.7 | 40.8 | 79.3 |
| 400 | 121.9 | 56.1 | 109.1 | 48.5 | 94.3 | 47.4 | 92.2 | 46.2 | 89.9 | 44.6 | 86.6 | 43.3 | 84.2 |
| 500 | 152.4 | 57.4 | 111.5 | 50.0 | 97.2 | 48.9 | 95.1 | 47.7 | 92.8 | 46.1 | 89.6 | 44.9 | 87.3 |

TABLE 2-43. Facilities Design Wind As A Function of Averaging Time ($t$) For A Peak Wind of 56.9 m/s (110.7 Knots) (1,000-Year Return Period) for VAFB And White Sands Missile Range.

| Height | | Facilities Design Wind as a Function of Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 (peak) | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 56.9 | 110.7 | 43.2 | 84.0 | 41.5 | 80.7 | 39.7 | 77.1 | 37.2 | 72.4 | 35.6 | 69.2 |
| 60 | 18.3 | 62.1 | 120.7 | 49.0 | 95.2 | 47.3 | 91.9 | 45.5 | 88.4 | 43.0 | 83.5 | 41.3 | 80.2 |
| 100 | 30.5 | 66.8 | 129.8 | 54.2 | 105.4 | 52.5 | 102.1 | 50.7 | 98.6 | 48.2 | 93.7 | 46.5 | 90.3 |
| 200 | 61.0 | 73.7 | 143.3 | 61.9 | 120.3 | 60.3 | 117.2 | 58.4 | 113.6 | 56.0 | 108.9 | 54.2 | 105.4 |
| 300 | 91.4 | 78.1 | 151.9 | 66.8 | 129.8 | 65.2 | 126.7 | 63.4 | 123.3 | 61.0 | 118.5 | 59.2 | 115.1 |
| 400 | 121.9 | 81.4 | 158.2 | 70.3 | 136.7 | 68.8 | 133.7 | 67.0 | 130.3 | 64.6 | 125.6 | 62.9 | 122.2 |
| 500 | 152.4 | 83.2 | 161.8 | 72.6 | 141.1 | 71.0 | 138.1 | 69.3 | 134.7 | 66.9 | 130.1 | 65.2 | 126.7 |

TABLE 2-44. Facilities Design Wind as a Function of Averaging Time ($t$) for A Peak Wind of 19.9 m/s (38.7 Knots) (10-Year Return Period) For EAFB.

| Height | | Facilities Design Wind as a Function of Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 (peak) | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 19.9 | 38.7 | 15.1 | 29.4 | 14.5 | 28.2 | 13.9 | 27.0 | 13.0 | 25.3 | 12.4 | 24.2 |
| 60 | 18.3 | 21.7 | 42.1 | 17.1 | 33.2 | 16.5 | 32.0 | 15.8 | 30.8 | 15.0 | 29.1 | 14.4 | 28.0 |
| 100 | 30.5 | 23.2 | 45.1 | 18.8 | 36.6 | 18.3 | 35.5 | 17.6 | 34.2 | 16.8 | 32.6 | 16.2 | 31.4 |
| 200 | 61.0 | 25.8 | 50.1 | 21.7 | 42.1 | 21.1 | 41.0 | 20.4 | 39.7 | 19.6 | 38.1 | 19.0 | 36.9 |
| 300 | 91.4 | 27.3 | 53.1 | 23.4 | 45.4 | 22.8 | 44.3 | 22.2 | 43.1 | 21.3 | 41.4 | 20.7 | 40.2 |
| 400 | 121.9 | 28.4 | 55.3 | 24.6 | 47.8 | 24.0 | 46.7 | 23.5 | 45.6 | 22.6 | 43.9 | 22.0 | 42.7 |
| 500 | 152.4 | 29.4 | 57.1 | 25.6 | 49.8 | 25.1 | 48.7 | 24.4 | 47.5 | 23.6 | 45.9 | 23.0 | 44.7 |

TABLE 2-45. Facilities Design Wind as a Function Of Averaging Time ($t$) for a Peak Wind Of 35.7 m/s (69.4 Knots) (100-Year Return Period) For EAFB.

| Height | | Facilities Design Wind as a Function of Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 (peak) | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 35.7 | 69.4 | 27.1 | 52.7 | 26.0 | 50.6 | 24.9 | 48.4 | 23.4 | 45.4 | 22.3 | 43.4 |
| 60 | 18.3 | 38.8 | 75.5 | 30.6 | 59.5 | 29.6 | 57.5 | 28.4 | 55.3 | 26.9 | 52.2 | 25.8 | 50.2 |
| 100 | 30.5 | 41.6 | 80.9 | 33.8 | 65.7 | 32.8 | 63.7 | 31.6 | 61.4 | 30.0 | 58.4 | 29.0 | 56.3 |
| 200 | 61.0 | 46.2 | 89.9 | 38.8 | 75.5 | 37.8 | 73.5 | 36.7 | 71.3 | 35.1 | 68.3 | 34.1 | 66.2 |
| 300 | 91.4 | 49.0 | 95.2 | 41.9 | 81.4 | 40.8 | 79.4 | 39.8 | 77.3 | 38.2 | 74.3 | 37.1 | 72.1 |
| 400 | 121.9 | 51.0 | 99.2 | 44.1 | 85.7 | 43.2 | 83.9 | 42.0 | 81.7 | 40.5 | 78.7 | 39.4 | 76.6 |
| 500 | 152.4 | 52.7 | 102.4 | 45.9 | 89.3 | 45.0 | 87.4 | 43.9 | 85.3 | 42.3 | 82.3 | 41.3 | 80.2 |

TABLE 2-46. Facilities Design Wind as a Function of Averaging Time ($t$) for a Peak Wind of 63.3 m/s (123.0 Knots) (1,000-Year Return Period) For EAFB.

| Height | | Facilities Design Wind as a Function of Averaging Times ($t$) in Minutes | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ft) | (m) | $t$ = 0 (peak) | | $t$ = 0.5 | | $t$ = 1 | | $t$ = 2 | | $t$ = 5 | | $t$ = 10 | |
| | | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) | (m/s) | (knots) |
| 33 | 10.0 | 63.3 | 123.0 | 48.0 | 93.3 | 46.1 | 89.7 | 44.1 | 85.7 | 41.4 | 80.5 | 39.6 | 76.9 |
| 60 | 18.3 | 68.8 | 133.8 | 54.3 | 105.5 | 52.4 | 101.8 | 50.4 | 98.0 | 47.6 | 92.6 | 45.7 | 88.9 |
| 100 | 30.5 | 73.7 | 143.2 | 59.8 | 116.2 | 58.0 | 112.7 | 55.9 | 108.7 | 53.2 | 103.4 | 51.3 | 99.7 |
| 200 | 61.0 | 82.0 | 159.3 | 68.8 | 133.8 | 67.0 | 130.3 | 65.0 | 126.3 | 62.2 | 121.0 | 60.3 | 117.2 |
| 300 | 91.4 | 86.8 | 168.7 | 74.2 | 144.2 | 72.4 | 140.7 | 70.4 | 136.9 | 67.7 | 131.6 | 65.7 | 127.8 |
| 400 | 121.9 | 90.4 | 175.8 | 78.1 | 151.9 | 76.4 | 148.6 | 74.5 | 144.8 | 71.8 | 139.5 | 69.9 | 135.8 |
| 500 | 152.4 | 93.4 | 181.5 | 81.4 | 158.2 | 79.7 | 154.9 | 77.7 | 151.1 | 75.1 | 145.9 | 73.1 | 142.1 |

2.2.11 Ground Winds for Runway Orientation Optimization. Runway orientation is influenced by a number of factors; for example, winds, terrain features, population interference, etc. In some cases, the frequency of occurrence of crosswind components of some significant speed has received insufficient consideration. Aligning the runway with the prevailing wind will not insure that crosswinds will be minimized. In fact, two common synoptic situations (one producing light easterly winds, and the other causing strong northerly winds) might exist in such a relationship that a runway oriented with the prevailing wind might be the least useful to an aircraft constrained by crosswind components. Two methods, one empirical and the other theoretical, based on the bivariate normal distribution for wind vectors, of determining the optimum runway orientation to minimize critical crosswind component speeds are available (Ref. 2-21).

In the empirical method, the runway crosswind components are computed for all azimuth and wind speed categories in the wind rose (Ref. 2-21). From these values, the optimum runway orientation can be selected that will minimize the risk of occurrence of any specified crosswind speed.

The theoretical method requires that the wind components are bivariate normally distributed; i.e., a vector wind data sample is resolved into wind components in a rectangular coordinate system, and the bivariate normal elliptical distribution is applied to the data sample of component winds. For example, let $x_1$ and $x_2$ be normally distributed variables with parameters ($x_1$, $s_1$) and ($x_2$, $s_2$). $x_1$ and $x_2$ are the respective means, while $s_1$ and $s_2$ are the respective standard deviations. Let $r$ be the correlation coefficient, which is a measure of the dependence between $x_1$ and $x_2$. Now, the bivariate normal density function is

$$p(x_1,x_2) = [2p\, s_1\, s_2 (1-r^2)^{1/2}]^{-1} * \exp\left[-[2(1-r^2)]^{-1}\left[\left(\frac{x_1-x_1}{s_1}\right)^2 - 2r\left(\frac{x_1-x_1}{s_1}\right)\left(\frac{x_2-x_2}{s_2}\right) + \left(\frac{x_2-x_2}{s_2}\right)^2\right]\right] . \qquad (2.23)$$

Let $a$ be an arbitrary angle in the rectangular coordinate system. From the statistics in the $(x_1,x_2)$ space, the statistics for any rotation of the axes of the bivariate normal distribution through any arbitrary angle $a$ may be computed (Ref. 2-22). Let $a$ denote the desired increments for which runway orientation accuracy is required; e.g., one may wish to minimize the probability of crosswinds with a runway orientation accuracy down to $a$ = 10º. This means we must rotate the bivariate normal axes through every 10º. It is only necessary to rotate the bivariate normal surface through 180º since the distribution is symmetric in the other two quadrants. Let $(y_1,y_2)$ denote the bivariate normal space after rotation.

This rotation process will result in 18 sets of statistics in the $(y_1,y_2)$ space. The quantity $y_1$ is the head wind component, while $y_2$ is the crosswind component. Since we are concerned with minimizing the probability of cross winds ($y_2$) only, we now examine the marginal distribution $p(y_2)$ for the 18 orientations (a). Since $p(y_1,y_2)$ is bivariate normal, the 18 marginal distributions $p(y_2)$ must be univariate normal:

$$p(y_2) = [s_2 (2p)^{1/2}]^{-1} \exp\left[-\frac{1}{2}\left[\frac{(y_2-x_2)}{s_2}\right]^2\right] . \qquad (2.24)$$

$x_2$ and $s_2$ are replaced by their sample estimates $Y_2$ and $S_{y2}$. Now, let

$$z = \frac{Y_2 - \overline{Y}_2}{S_{y_2}} , \qquad (2.25)$$

where $y_2$ is the critical crosswind of interest and $S_{y_2}$ is the standard deviation of the $y_2$ with respect to its mean $\bar{y}_2$. The quantity $z$ is a normal variable, and the probability of its exceedence is easily calculated from the tables of the standard normal integral. Since a right or left crosswind ($y_2$) is a constraint to an aircraft, the critical region (exceedence region) for the normal distribution is two-tailed; i.e., we are interested in twice the probability of exceeding $|y_2|$. Let this probability of exceedence or risk equal $R$. Now, the orientation for which $R$ is a minimum is the desired optimum runway orientation. The procedure described may be used for any station. Only parameters estimated from the data are required as input. Consequently, many runways and locations may be examined rapidly.

Either the empirical or theoretical method may be used to determine an aircraft runway orientation that minimizes the probability of critical crosswinds. Again, it is emphasized that the wind components must be bivariate normally distributed to use the theoretical method. In practical applications, the following steps are suggested.

1. Test the component wind samples for bivariate normality if these samples are available.

2. If the component winds are available and cannot be rejected as bivariate normal using the bivariate normal goodness-of-fit test, use the theoretical method since it is more expedient and easily programmed.

3. If the component wind data samples are not available and there is doubt concerning the assumption of bivariate normality of the wind components, use the empirical method.

## 2.3 <u>In-flight Winds</u>.

2.3.1 Introduction. In-flight wind speed profiles are used in vehicle design studies primarily to establish structural and control system capabilities and to compute performance requirements. The in-flight wind speeds selected for vehicle design may not represent the same percentile value as the design surface wind speed. The selected wind speeds (in-flight and surface) are determined by the desired on-pad stay time and vehicle launch capabilities and can differ in the percentile level since the in-flight and surface wind speeds differ in degree of persistence for a given reference time period, they can be treated as being statistically independent for engineering design purposes.

Wind profile information for in-flight design studies is presented in two basic forms: discrete or synthetic profiles and measured profile samples. There are certain limitations to each of these wind input forms, and their utility in design studies depends upon a number of considerations such as (1) accuracy of basic measurements, (2) complexity of input to vehicle design, (3) economy and practicality for design use, (4) ability to represent significant features of the wind profile, (5) statistical assumption versus physical representation of the wind profile, (6) ability of input to ensure control system and structural integrity of the vehicle, and (7) flexibility for use in design trade-off studies.

An accurate and adequate number of measured wind profiles are necessary for developing a valid statistical description of the wind profile. Fortunately, current records of data from some locations (KSC in particular) fulfill these requirements, although a continuing program of data acquisition is vital to further enhance the confidence of the statistical information generated. Various methods and sensors for obtaining in-flight profiles include the rawinsonde, radar wind profiler, the FPS-16 radar/jimsphere, and the rocketsonde. The statistical analyses performed on the in-flight wind profiles provide detailed descriptions of the upper winds and an understanding of the profile characteristics, such as temporal and height variations, as well as indications of the frequency and the persistence of transient meteorological systems.

The synthetic type of wind profile is the oldest method used to present in-flight design wind data. The synthetic wind profile data are presented in this document because this method of presentation provides a reasonable approach for most design studies when properly used, especially during the early design periods. Also, the concept of synthetic wind profiles is generally understood and employed in most aerospace organizations for design computations. The synthetic wind profile includes the wind speed, wind speed change, maximum wind layer thickness, and gusts that are required to establish vehicle design structural and control system values.

Currently, launch vehicles for use at various launch sites and in comprehensive space research mission and payload configurations are designed by use of synthetic vector wind and wind shear models with regard to specific wind direction. However, if a vehicle is not restricted to a given launch site, and flight azimuths, and a specific configuration and mission, wind components (head, tail, left cross, or right cross) are often used. Component wind profiles are sometimes used, and, for a given percentile, the magnitudes of component winds are equal to or less than those of the scalar winds. Component or directionally dependent winds should not be employed in initial design studies unless specifically authorized by the cognizant design organization. Vector wind and vector wind shear models may be more applicable and were used for the space shuttle vehicle.

Selection of a set of detailed wind profiles for final design verification and launch delay risk calculations requires the matching of vehicle simulation resolution and technique to frequency or information content of the profile. Detailed wind profile data sets for design verification use are available for KSC, FL, and VAFB, CA (see section 2.3.12.1). Selected samples of detailed wind profiles are available for other locations.

The synthetic wind profile provides a conditionalized wind shear/gust state with respect to the given design wind speed. Therefore, in concept, the synthetic wind profile should produce a vehicle design which has a launch delay risk not greater than a specified value which is generally the value associated with the design wind speed. This statement, although generally correct, depends on the control system response characteristics, the vehicle structural integrity, etc. A joint condition of wind shear, gust, and speeds is given in selection of detailed wind profiles for design verification. Therefore, the resulting launch delay risk for a given vehicle design is the specified value of risk computed from the vehicle responses associated with the various profiles. For the synthetic profile, a vehicle in-flight wind speed capability and maximum launch delay risk may be stated which is conditional upon the wind/gust design values. However, for the selection of detailed wind profiles, only a vehicle launch risk value may be given since the wind characteristics are treated as a joint event. These two differences in philosophy should be understood to avoid misinterpretation of vehicle response calculation comparisons. In both cases, allowance for dispersions in vehicle characteristics should be made prior to flight simulation through the wind profiles and establishment of vehicle design response or operational launch delay risk values. The objective is to ensure that an aerospace vehicle will accommodate the desired percentage of wind profiles or conditions in its non-nominal flight mode (i.e., engine out, etc.).

2.3.2 Wind Aloft Climatology. The development of design wind speed profiles and associated shears and gusts requires use of the measured wind speed and wind direction data collected at the area of interest for some reasonably long period of time, i.e., 10 years or longer. The subject of wind climatology for an area, if treated in detail, would make up a voluminous document. The intent here is to give a brief treatment of selected topics that are frequently considered in aerospace vehicle development and operation problems and provide references to more extensive information.

Considerable data summaries (monthly and seasonal) exist on wind aloft statistics for the world. However, it is necessary to interpret these data in terms of the engineering design problem and design philosophy. For example, wind requirements for performance calculations relative to aircraft fuel consumption requirements must be derived for the specific routes and design reference period. Such data are available on request.

2.3.3 Wind Component Statistics. Wind component statistics are used in mission planning to provide information on the probability of exceeding a given wind speed in the pitch or yaw planes and to bias the tilt program at a selected launch time. The vector wind and vector wind shear model discussed in section 2.3.10 is directly applicable to the description of these input data.

The wind component statistics can be computed for various launch azimuths (15º intervals were selected by MSFC) for each month for the pitch plane (range) and yaw plane (cross range) at KSC and VAFB, CA. References 2-23 through 2-25 contain information on the statistical distributions of wind speeds and vector wind components for the various vehicle flight centers and test ranges.

2.3.3.1 Upper Wind Correlations. Coefficients of correlations of wind components between altitude levels with means and standard deviations at altitude levels may be used in a statistical model to derive representative wind profiles. A method of preparing synthetic wind profiles by use of correlation coefficients between wind components is described in reference 2-26. In addition, these correlation data are applicable to certain statistical studies of vehicle responses (Ref. 2-27).

Data on correlations of wind between altitude levels for various geographical locations are presented in references 2-28, 2-29, and 2-30. The reports give values of the interlevel and intralevel coefficients of linear correlations between wind components. The linear correlation coefficients between altitudes within the 10- to 15-km altitude region are very high, but decrease with greater altitude separation.

Correlations between wind components separated by a horizontal distance are now available. The reader is referred to the work of Buell (refs. 2-31 and 2-32) for a detailed discussion of the subject.

2.3.3.2 Thickness of Strong Wind Layers. Wind speeds in the middle latitudes generally increase with altitude to a maximum between 10- and 14-km. Above 14 km, the wind speeds decrease with altitude, then increase at higher altitude, depending upon season and location. Frequently, these winds exceed 50 m/s in the jet stream, a core of maximum winds over the midlatitudes in the 10- to 14-km altitudes. The vertical extent of the core of maximum winds, or the sharpness of the extent of peak winds on the wind profile, is important in some vehicle design studies. For information concerning the thickness of strong wind layers, the reader is referred to reference 2-33.

Table 2-47 shows design values of vertical thickness (based on maximum thickness) of the wind layers for wind speeds for KSC. Similar data for VAFB are given in Table 2-48. At both ranges, the thickness of the layer decreases with increase of wind speed; that is, the sharpness of the wind profile in the vicinity of the jet core becomes more pronounced as wind speed increases.

TABLE 2-47. Design Thickness For Strong Wind Layers At KSC.

| Quasi-Steady-State Wind Speed ($\pm 5$ ms$^{-1}$) | Maximum Thickness (km) | Altitude Range (km) |
|---|---|---|
| 50 | 4 | 8.5 to 16.5 |
| 75 | 2 | 10.5 to 15.5 |
| 92 | 1 | 10.0 to 14.0 |

TABLE 2-48. Design Thickness For Strong Wind Layers At VAFB, CA.

| Quasi-Steady-State Wind Speed ($\pm 5$ ms$^{-1}$) | Maximum Thickness (km) | Altitude Range (km) |
|---|---|---|
| 50 | 4 | 8.0 to 16 |
| 75 | 2 | 9.5 to 14 |

2.3.3.3 Exceedance Probabilities. The probability of in-flight winds exceeding or not exceeding some critical wind speed for a specified time duration may be of considerable importance in mission planning, and, in many cases, more information than just the occurrence of critical winds is desired. If a dual launch, with the second vehicle being launched 1 to 3 days after the first, is planned and if the launch opportunity extends over a 10-day period, what is the probability that winds below (or above) critical levels will last for the entire 10 days? What is the probability of 2 or 3 consecutive days of favorable winds in the 10-day period? Suppose the winds are favorable on the scheduled launch day, but the mission is delayed for other reasons. Now, what is the probability that the winds will remain favorable for 3 or 4 more days? Answers to these questions could also be used for certain design considerations involving specific vehicles prepared for a given mission and launch window. A body of statistics is available from the NASA-MSFC's Earth Science and Applications Division which can be used to answer these and possibly other related questions. An example of the kind of wind persistence statistics that are available is given in figure 2-9. This figure gives the probability of the maximum wind speed in the 10- to 15-km region being less than, equal to, or greater than 50 and 75 ms$^{-1}$, for various multiples of 12 hours for the month of January. Thus, for example, there is approximately an 18-percent chance that the wind speed will be greater than or equal to 50 m/s for 10 consecutive 12-h periods in January. The random series is plotted as $p^k$, for $k$ = 1,2,..., 12-h periods.

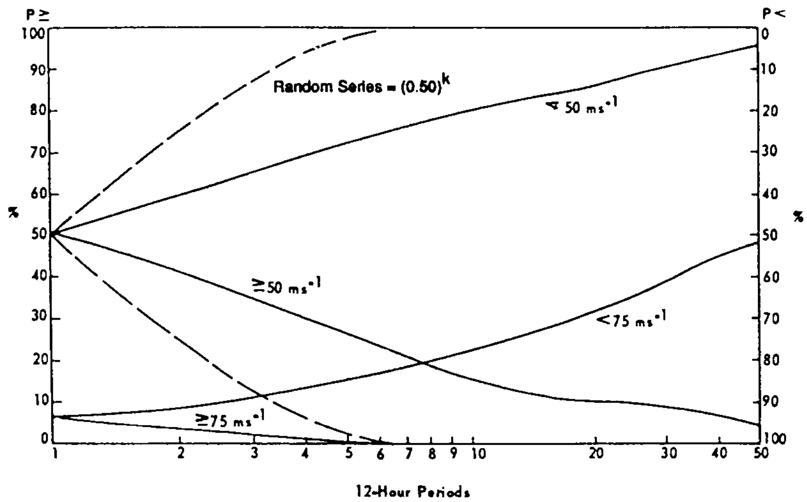



FIGURE 2-9. Probability of the Maximum Wind Speed in the 10- to 15-Km Layer Being Less Than, Equal to, or Greater Than Specified Values For k-Consecutive 12-H Periods During January At KSC.

2.3.3.4 Design Scalar Wind Speeds (10- to 15-km Altitude Layer). The distributions of design scalar wind speed in the 10- to 15-km altitude layer over the United States are shown in figure 2-10 for the 95-percentile value and figure 2-11 for the 99-percentile values. The location of local maximum in the isopleths (maximum wind speeds) is shown by heavy lines with arrows. These winds occur at approximately the level of maximum dynamic pressure for most aerospace vehicles.

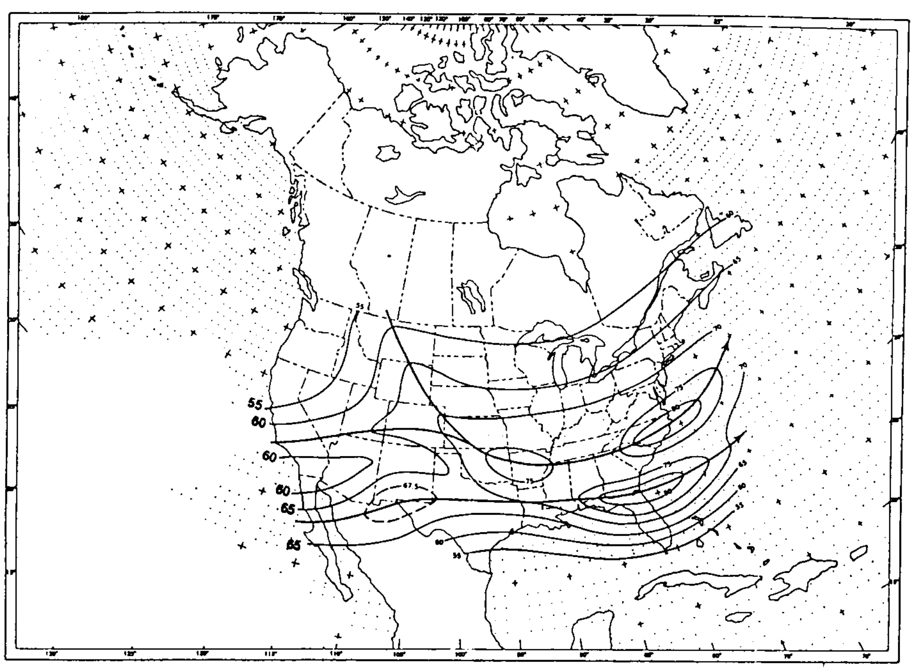


FIGURE 2-10. Design Scalar Wind Speeds (m/s) 95-Percentile Envelope Analysis Prepared From Windiest Month And Maximum Winds in the 10- To 15-Km Layer.

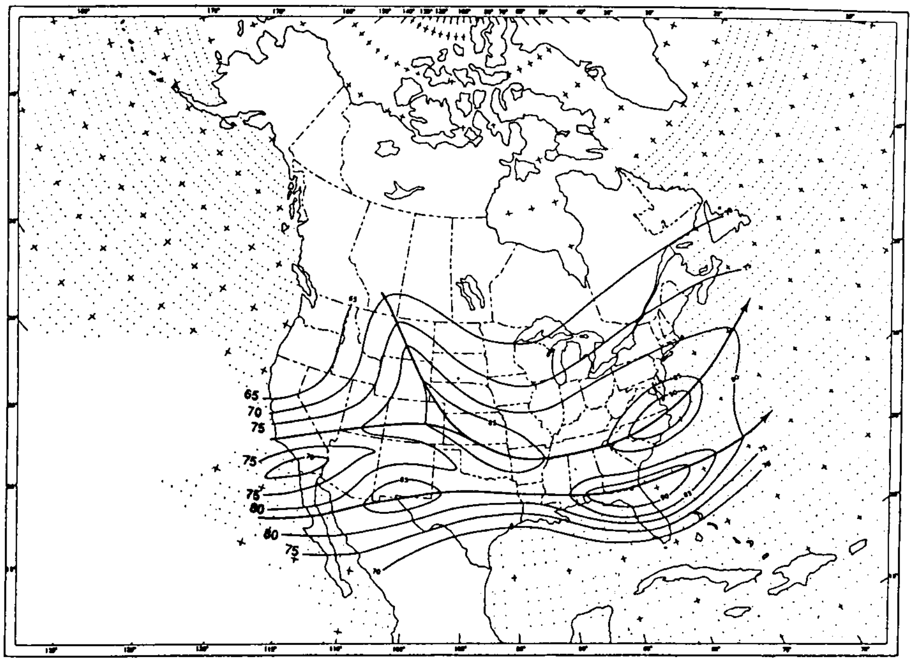



FIGURE 2-11. Design Scalar Wind Speeds (m/s) 99-Percentile Envelope Analysis Prepared From Windiest Month And Maximum Winds In The 10- To 15-Km Layer.

2.3.3.5 Temporal Wind Changes. Atmospheric wind fields change with time. Significant wind direction and speed changes can occur over time scales as short as a few minutes or less. There is no upper bound limit on the time scale over which the wind field can change. To develop real time wind biasing programs for aerospace vehicle control purposes, which involve the use of wind profiles observed a number of hours prior to launch, it is necessary that consideration be given to the changes in wind speed and direction that can occur during the time elapsed from entering the biasing profile into the vehicle control system logic to the time of launch. If the observed wind profile 8 h prior to launch is to be used as a wind biasing profile, then consideration should be given to the dispersions in wind direction and speed that could occur over this period of time. Wind speed and direction change data are also useful for mission operation purposes. Results of studies conducted by the NASA-MSFC's Earth Science and Applications Division to define these dispersions in a statistical context are presented herein. Specialized data bases containing pairs of FPS-16 Jimsphere measured detail wind profiles over time periods of 2 to 12 h are available upon request to the Environments Group, ED44, Marshall Space Flight Center, AL 35812.

To account for the differences between the dynamics of the flow in the atmospheric boundary layer and the free atmosphere, the atmosphere over KSC is usually partitioned at the 2-km level in studies of the temporal changes in the wind field. Below the 2-km level, the flow is significantly influenced by the surface of the Earth and is predominantly a turbulent flow. In the free atmosphere above the 2-km level for terrain similar to KSC, the flow is, for all practical purposes, free of the effects of the surface boundary layer of the Earth. In mountainous areas this level can vary considerably.

Figures 2-12 and 2-13 contain idealized 99-percent wind direction and speed changes as a function of elapsed time and observed or referenced wind speed for altitudes between 150 m and 2 km for KSC. The wind speed may increase or decrease from the reference profile value; thus, envelopes of each category are presented in figure 2-13. Figures 2-14 and 2-15 are the idealized 99-percent wind direction and speed changes as a function of elapsed time and observed or reference wind speed for altitudes between 2 and 16 km.

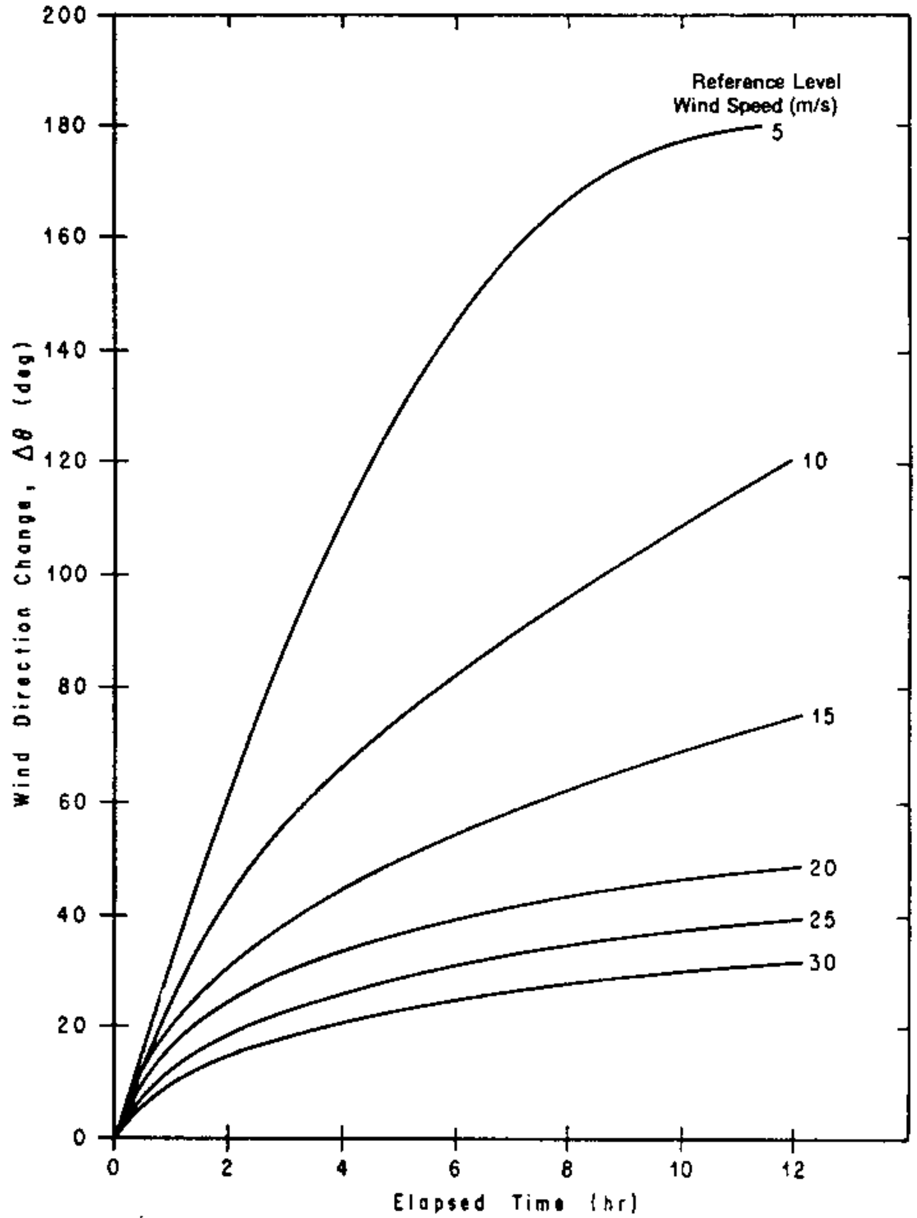



FIGURE 2-12. Idealized 99-Percent Wind Direction Change as a Function of Time and Wind Speed in the 150-m To 2-Km Altitude Region Of KSC.

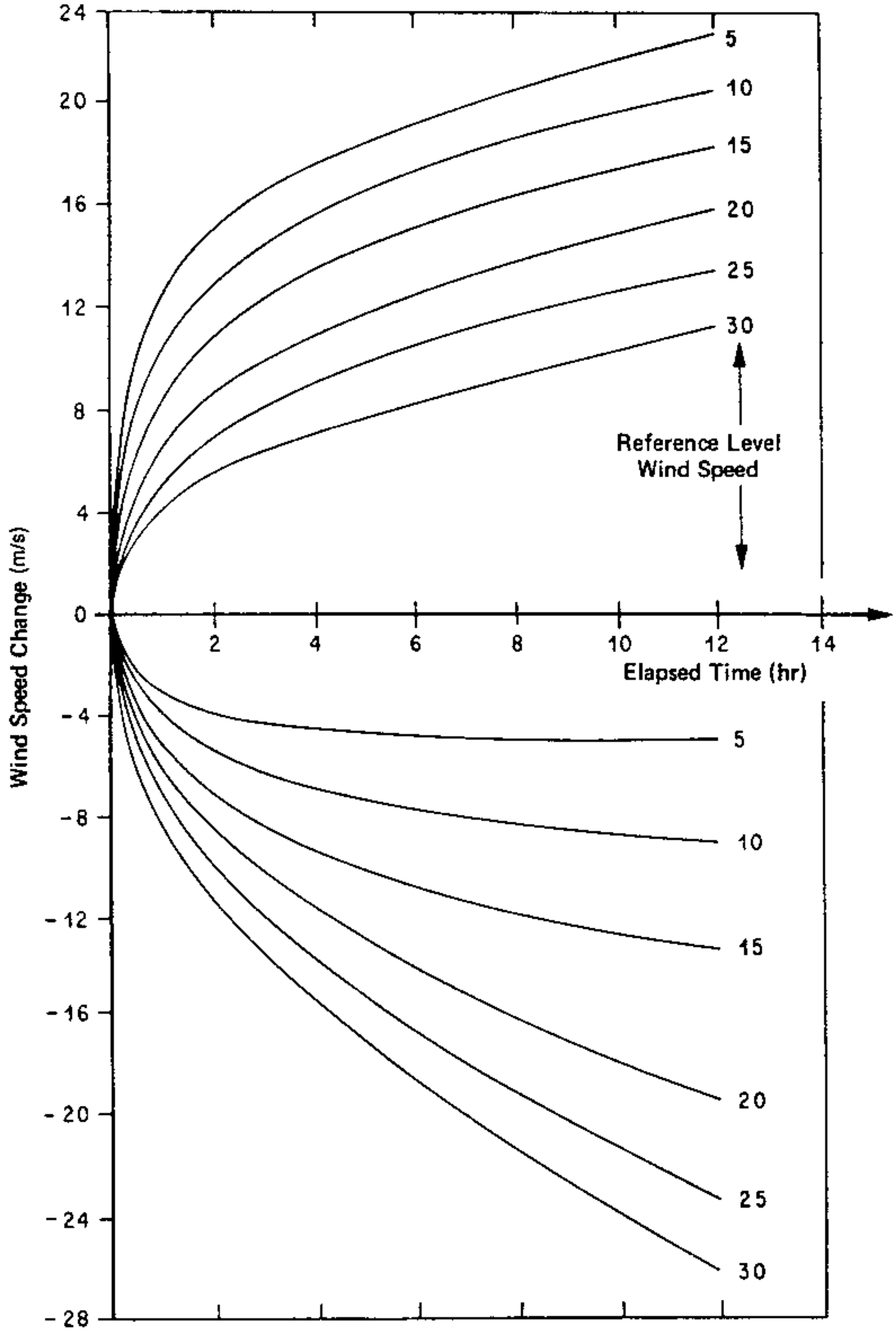



FIGURE 2-13. Idealized 99-Percent Wind Speed Change as a Function of Time and Wind Speed in the 150-m To 2-Km Altitude Region Of KSC.

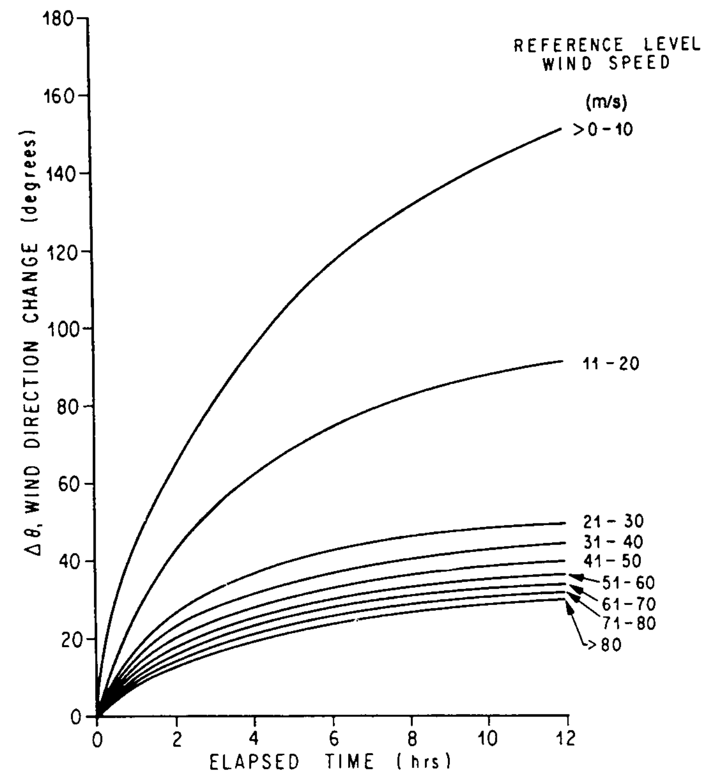



FIGURE 2-14. Idealized 99-Percent Wind Direction Change As A Function Of Time and Wind Speed In The 2- To 16-Km Region Of KSC.

The preceding data are applicable only to the KSC launch area because differences are known to exist in the data for other geographical locations. Conclusions should not be drawn relative to frequency content and phase relationships of the wind profile since the data given herein provide only envelope conditions for ranges of speed and direction changes. Direction correlations have not been developed between the changes of wind direction and wind speed.

Additional information concerning wind speed and direction changes can be found in reports by Camp and Susko (Ref. 2-34) and Camp and Fox (Ref. 2-35).

Temporal vector wind change at KSC and VAFB has been studied by Adelfang (refs. 2-36 and 2-37). The joint distribution of the four variables represented by the *u* and *v* components of the wind vector at an initial time and after a specified elapsed time is hypothesized to be quadravariate normal. The 14 statistics of this distribution are presented according to monthly reference period for altitudes from 0 to 27 km. These statistics are used to calculate percentiles of the theoretical distribution of wind component change with respect to time (univariate normal distribution), the joint distribution of wind component change (bivariate normal), the modulus of vector wind change (Rayleigh), and the vector wind at a future time given the vector wind at an initial time (conditional bivariate normal); the large body of statistics contained in these references are not repeated herein. For the purpose of illustrating the application of these statistics, the 95-percentile vector wind change ellipses for time intervals of 12, 24, 36, 48, 60, and 72 h at 6, 12, and 18 km during April at KSC and during January at VAFB have been calculated. Each ellipse illustrated in figure 2-16 was calculated from the bivariate normal statistics of vector wind change given in the referenced reports; each ellipse encompasses 95 percent of the wind change expected for the indicated time interval. The methodology for calculation of wind or wind change ellipses for any percentile is described by Smith (Ref. 2-38). The wind change ellipses illustrated in figure 2-16 clearly indicate the strong variation of wind change for time intervals less than 48 hours, and the relatively large wind change for VAFB.

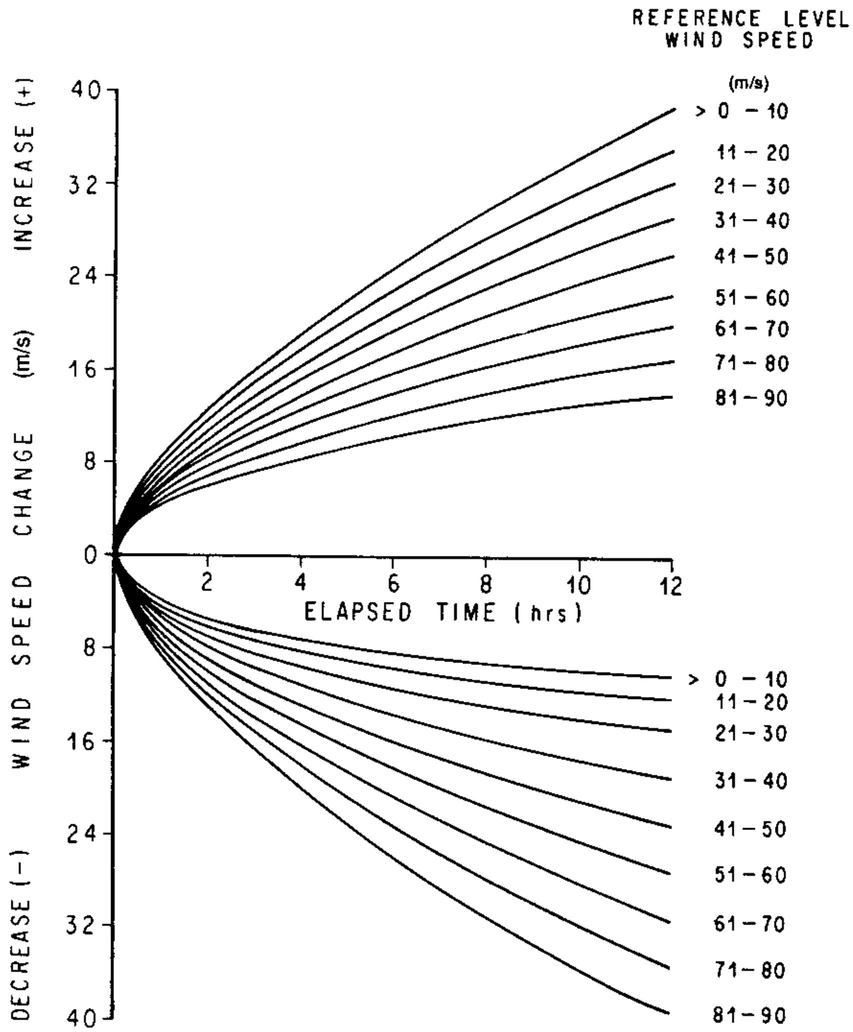



FIGURE 2-15. Idealized 99-Percent Wind Speed Change as a Function of Time and Wind Speed In The 2- To 16-Km Region Of KSC.

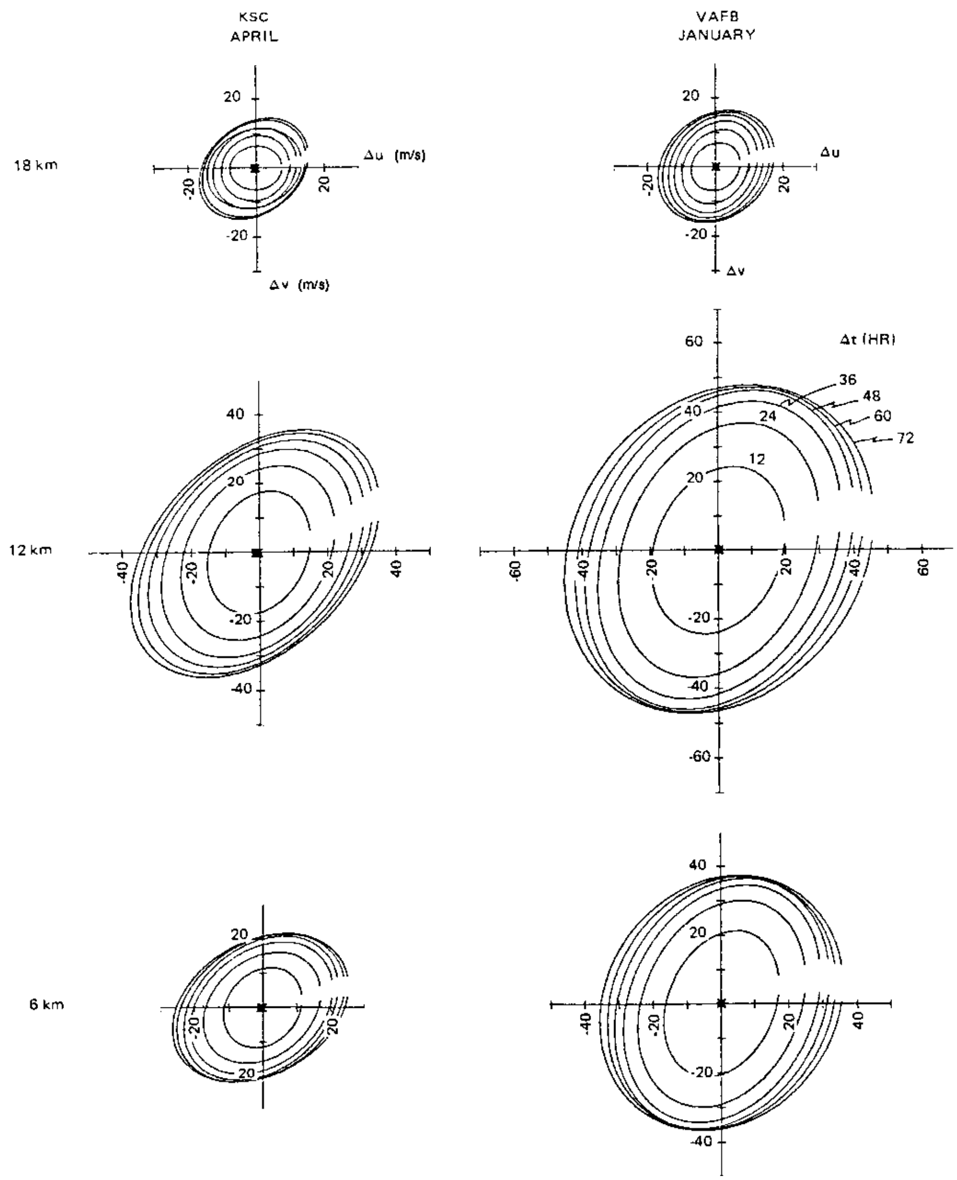



FIGURE 2-16. April KSC And January VAFB 95-Percentile Wind Change (Δu And Δ*v*) Ellipses at 6, 12, and 18 Km Altitude for Time Intervals Of 12, 24, 36, 48, 60, and 72 H.

2.3.4 Wind Speed Profiles for Biasing Tilt Program. In attempting to maintain a desired flight path for an aerospace vehicle through a strong wind region, the vehicle control system could introduce excessive bending moments and orbit anomalies. To reduce this problem, it is sometimes desirable to wind bias the pitch program; that is, to tilt the vehicle sufficiently to produce the desired flight path and minimize dynamic pressure level loads with the expected wind profile. Since most in-flight strong winds over KSC are winter westerlies, it is sometimes expedient to use the monthly or seasonal pitch plane median wind speed profile for bias analyses.

Head and tail wind components and right and left crosswind components from 0- to 70-km altitudes can be computed for any flight azimuth used at KSC or VAFB. For applications where both pitch and yaw biasing are used, monthly vector mean winds may be more efficient for wind biasing. Such statistics can be made available upon request, or see reference 2-38 and section 2.3.10 and reference 2-55 for a new wind biasing technique.

2.3.5 Design Wind Speed Envelopes. The wind data given in section 2.3.5.1 are not expected to be exceeded by the given percentages of time (time as related to the observational interval of the data sample) based upon the windiest monthly reference period. To obtain the profiles, monthly frequency distributions are combined for each percentile level to give the envelope over all months. The profiles represent horizontal wind flow referenced to the Earth's surface. Vertical wind flow is negligible except for that associated with gusts or turbulence. The scalar wind speed envelopes are normally applied without regard to flight directions to establish the initial design requirements. Directional wind criteria for use with the synthetic wind profile techniques should be applied with care and specific knowledge of the vehicle mission and flight path, since severe wind constraints could result for other flight paths and missions.

2.3.5.1 Scalar Wind Speed Envelopes. Scalar wind speed profile envelopes are presented in Tables 2-49 through 2-53. These are idealized steady-state scalar wind speed profiles for four active or potential operational aerospace vehicle launch or landing sites; i.e., KSC, FL, VAFB, CA; White Sands Missile Range, NM; and Edwards AFB, CA. Table 2-53 provides data which envelopes the 95- and 99-percentile steady-state scalar wind speed profile for the same four locations. They are applicable to design criteria when initial design or operational capability has not been restricted to specific launch and landing sites or may involve several geographical locations. However, if the specific geographical location for application has been determined as being near one of the four referenced sites then the relevant data should be applied.

These tables provide design nondirectional wind data for various percentiles; therefore, the specific percentile wind speed envelope applicable to design should be specified in the appropriate space vehicle specification documentation. For engineering convenience, the design wind speed profile envelopes are given as linear segments between altitude levels; therefore, the tabular values can be linearly interpolated.

2.3.5.2 Vector Wind Models. Wind is a vector quantity having a magnitude and direction. A coordinate system and a statistical model are required. The bivariate normal probability distribution is used to model the wind at discrete altitudes. Wind measurements are recorded in terms of wind direction and magnitude. The wind direction is measured in degrees clockwise from true north and is the direction from which the wind is blowing. The wind magnitude (the modulus of the vector) is the scalar quantity and is referred to as wind speed or scalar wind. The standard meteorological coordinate system (fig. 2-17) has been chosen for the wind statistics and tables of statistical parameters.

TABLE 2-49. Scalar Wind Speed *W* (m/s) Steady-State Envelopes As Functions Of Altitude *H* (Km) For Various Probabilities *P* (%) For KSC.

| Altitude (km) | Percentile | | | | |
|---|---|---|---|---|---|
| | 50 | 75 | 90 | 95 | 99 |
| 1 | 8 | 13 | 16 | 19 | 24 |
| 6 | 23 | 31 | 39 | 44 | 52 |
| 11 | 43 | 55 | 66 | 73 | 88 |
| 12 | 45 | 57 | 68 | 75 | 92 |
| 13 | 43 | 56 | 67 | 74 | 86 |
| 20 | 7 | 12 | 17 | 20 | 25 |
| 23 | 7 | 12 | 17 | 20 | 25 |
| 40 | 43 | 57 | 70 | 78 | 88 |
| 50 | 75 | 83 | 91 | 95 | 104 |
| 58 | 85 | 96 | 106 | 112 | 123 |
| 60 | 85 | 96 | 106 | 112 | 123 |
| 75 | 15 | 22 | 28 | 30 | 37 |
| 80 | 15 | 22 | 28 | 30 | 37 |

TABLE 2-50. Scalar Wind Speed *W* (M/S) Steady-State Envelopes As Functions Of Altitude *H* (Km) For Various Probabilities *P* (%) For VAFB, CA.

| Altitude (km) | Percentile | | | | |
|---|---|---|---|---|---|
| | 50 | 75 | 90 | 95 | 99 |
| 1 | 7 | 10 | 13 | 15 | 19 |
| 6 | 20 | 29 | 36 | 41 | 50 |
| 11 | 31 | 43 | 53 | 60 | 73 |
| 12 | 32 | 44 | 55 | 62 | 79 |
| 13 | 32 | 44 | 55 | 62 | 79 |
| 20 | 6 | 10 | 14 | 17 | 26 |
| 23 | 6 | 10 | 14 | 17 | 26 |
| 40 | 55 | 67 | 82 | 90 | 105 |
| 50 | 79 | 96 | 111 | 120 | 132 |
| 58 | 83 | 107 | 128 | 140 | 164 |
| 60 | 83 | 107 | 128 | 140 | 164 |
| 75 | 50 | 65 | 87 | 98 | 118 |
| 80 | 50 | 65 | 87 | 98 | 118 |

TABLE 2-51. Scalar Wind Speed *W* (m/s) Steady-State Envelopes As Functions Of Altitude *H* (Km) For Various Probabilities *P* (%) For White Sands Missile Range, NM.

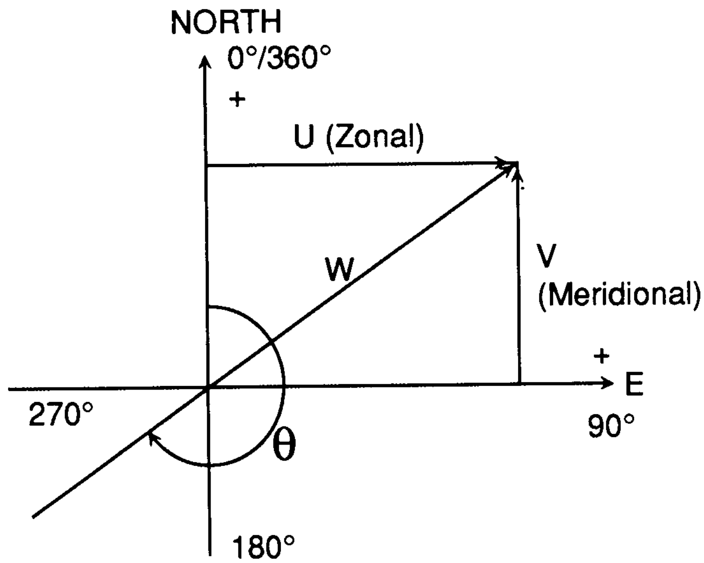
| *P* = 50 | | *P* = 75 | | *P* = 90 | | *P* = 95 | | *P* = 99 | |
|---|---|---|---|---|---|---|---|---|---|
| *H* | *W* | *H* | *W* | *H* | *W* | *H* | *W* | *H* | *W* |
| 1 | 4 | 1 | 7 | 1 | 11 | 1 | 13 | 1 | 22 |
| 2 | 5 | 2 | 8 | 2 | 12 | 2 | 15 | 2 | 22 |
| | | | | | | 7 | 50 | 7 | 68 |
| | | 9 | 45 | 8 | 49 | 9 | 67 | 9 | 88 |
| 11 | 42 | 10 | 53 | 11 | 71 | 11 | 76 | | |
| 13 | 42 | 12 | 55 | 13 | 63 | 12 | 78 | 14 | 88 |
| | | | | 15 | 45 | 15 | 52 | 15 | 69 |
| 20 | 10 | 20 | 14 | 20 | 20 | 20 | 24 | 20 | 41 |
| 23 | 10 | 23 | 14 | 23 | 20 | 23 | 24 | 23 | 41 |
| 50 | 85 | 50 | 104 | 50 | 120 | 50 | 130 | 50 | 150 |
| 60 | 85 | 60 | 104 | 60 | 120 | 60 | 130 | 60 | 150 |
| 75 | 60 | 75 | 77 | 75 | 93 | 75 | 102 | 75 | 120 |
| 80 | 60 | 80 | 77 | 80 | 93 | 80 | 102 | 80 | 120 |

TABLE 2-52. Scalar Wind Speed *W* (M/S) Steady-State Envelopes As Functions Of Altitude *H* (Km) For Various Probabilities *P* (%) For EAFB, CA.

| *P* = 50 | | *P* = 75 | | *P* = 90 | | *P* = 95 | | *P* = 99 | |
|---|---|---|---|---|---|---|---|---|---|
| *H* | *W* | *H* | *W* | *H* | *W* | *H* | *W* | *H* | *W* |
| 1 | 8 | 1 | 11 | 1 | 16 | 1 | 17 | 1 | 25 |
| 2 | 8 | 2 | 12 | 2 | 16 | 2 | 18 | 2 | 28 |
| | | | | 5 | 30 | 5 | 36 | 5 | 56 |
| 10 | 29 | | | 10 | 51 | 10 | 61 | 10 | 77 |
| 12 | 32 | 11 | 44 | 11 | 56 | | | 12 | 77 |
| 15 | 25 | 13 | 39 | 12 | 56 | 12 | 61 | 14 | 65 |
| 18 | 13 | 17 | 21 | 17 | 28 | 16 | 38 | 16 | 43 |
| 20 | 9 | 20 | 13 | 20 | 19 | 20 | 23 | 20 | 30 |
| 23 | 9 | 23 | 13 | 23 | 19 | 23 | 23 | 23 | 30 |
| 50 | 85 | 50 | 104 | 50 | 120 | 50 | 130 | 50 | 150 |
| 60 | 85 | 60 | 104 | 60 | 120 | 60 | 130 | 60 | 150 |
| 75 | 60 | 75 | 77 | 75 | 93 | 75 | 102 | 75 | 120 |
| 80 | 60 | 80 | 77 | 80 | 93 | 80 | 102 | 80 | 120 |

TABLE 2-53. Scalar Wind Speed *W* (M/S) Steady-State Envelopes As Functions Of Altitude *H* (Km) For Various Probabilities *P* (%) For All Four Locations.

| *P* = 95 | | | | *P* = 99 | | | |
|---|---|---|---|---|---|---|---|
| *H* | *W* | *H* | *W* | *H* | *W* | *H* | *W* |
| 1 | 22 | 17 | 44 | 1 | 28 | 15 | 70 |
| 3 | 31 | 20 | 29 | 3 | 38 | 20 | 41 |
| | | 23 | 29 | 5 | 56 | 23 | 41 |
| 6 | 54 | 50 | 150 | 6 | 60 | 50 | 170 |
| | | 60 | 150 | 7 | 68 | 60 | 170 |
| 10 | 75 | 75 | 120 | 9 | 88 | 75 | 135 |
| 11 | 76 | 80 | 120 | 11 | 88 | 80 | 135 |
| 12 | 78 | | | 12 | 92 | | |
| 13 | 74 | | | 13 | 88 | | |
| | | | | 14 | 88 | | |




Definitions:

*U* is the zonal wind component, positive west to east in units, m/s.
*V* is the meridional wind component, positive south to north in units, m/s.
*W* is the wind speed in units, m/s.
*q* is the wind direction measured in degrees clockwise from true north and is the direction from which the wind is blowing.
$U = -W \cos q$ ,
$V = -W \sin q$ ,

where $0^o \leq q \leq 360^o$

FIGURE 2-17. Meteorological Coordinate System.

The bivariate normal probability density function (BNpdf) can be expressed in cartesian and polar coordinates. Using population notations for the required five statistical parameters, the BNpdf in the usual mathematical cartesian coordinates is:

$$f(\bar{x},\bar{y}) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}} \exp\left[\frac{1}{2(1-\rho^2)}\left[\frac{(X-\bar{X})^2}{\sigma_x^2} - \frac{2\rho\,(X-\bar{X})(Y-\bar{Y})}{\sigma_x\sigma_y} + \frac{(Y-\bar{Y})^2}{\sigma_y^2}\right]\right] , \tag{2.26}$$

where $-\infty \leq X \leq \infty$ and $-\infty \leq Y \leq \infty$. This function is completely described by the five parameters: the means *X* and *Y*, the standard deviations $s_x$ and $s_y$, and the linear correlation coefficient, *r*, between the variables *x* and *y*.

The contours of equal probability density form a family of concentric ellipses with respect to the centroid located at the point $\{\bar{x}, \bar{y}\}$. The probability contained within a contour of equal probability density is obtained by integrating the probability density function over the region defined by the contour.

This integration is obtained in closed form. The result is called a probability ellipse for the assigned probability area.

Using the properties of the bivariate normal probability distribution to model the wind as a vector quantity at discrete altitudes, many other probability functions can be derived. All that is required are the five bivariate normal statistical parameters with respect to an orthogonal coordinate system. The practical system of equations are given by Smith (Ref. 2-38) and repeated in the range reference atmosphere publications (Ref. 2-23) with illustrations. In terms of wind statistics, some of these properties are:

1. The five statistical parameters that have been computed with respect to a meteorological zonal and meridional coordinate system can be rotated to any other orthogonal coordinate system and the properties of the bivariate normal distribution still holds.

2. The wind components are univariate normally distributed. Percentile values and interpercentile values can be computed.

3. The conditional distribution of one wind component given the other is univariate normally distributed.

4. The sum and difference of bivariate normally distributed variates are univariate normally distributed.

5. The probability ellipse that contains $p$-percent of the wind vectors can be computed.

6. The probability density function for wind direction can be derived, and, by numerical integration, the probability for wind direction within any assigned limits can be computed.

7. The conditional probability density function for wind speed given a wind direction can be obtained.

8. The conditional probability distribution function for wind speed given a wind direction can be obtained.

9. The probability density function for wind speed can be derived as a generalized Rayleigh distribution (Ref. 2-38). It is expressed as a series of the sum of products of the modified Bessel function.

The equations for the above functions are given in the most general form for all five statistical parameters for the bivariate normal distribution. For assumptions such as independent variates, zero means and equal variances are treated as special cases. With the advent of modern computers, these functions can be readily evaluated and graphic illustrations made. Some of these probability functions are presented in this subsection because of their important role in wind vector modeling.

2.3.5.2.1 Bivariate Normal Wind Parameters. There are several publications (refs. 2-23, 2-24, 2-25, and 2-51) that contain the bivariate normal wind statistical parameters versus altitude. All of these reports give tabulations for the five bivariate normal parameters with respect to the meteorological coordinate system.

The five statistical parameters are:

$\overline{U}$ = the monthly mean zonal wind component (m/s)

$\overline{V}$ = the monthly mean meridional wind component (m/s)

$S_u$ = the standard deviation with respect to the monthly mean for the zonal wind component (m/s)

$S_v$ = the standard deviation with respect to the monthly mean for the meridional wind component (m/s)

$R(U,V)$ = the correlation coefficient between the two components.

Tables 2-54 through 2-57 are taken from reference 2-51. These statistical parameters are for KSC, February and July; and for VAFB, December and July. For the altitude region 0 to 27 km, these parameters are from twice daily, serially complete rawinsonde wind measurements. The altitudes from 28 to 86 km are from rocketsonde wind measurements. For KSC, the period of record is 19 years, and, for VAFB, the period of record is 10 years. These months for the respective sites are chosen for illustration because they reasonably envelop the winds for both sites for all months.

For aerospace vehicle applications, it is often desired to express the wind statistics with respect to the vehicle flight azimuth.

By using coordinate rotation equations, these five statistical parameters can be calculated with respect to any orthogonal coordinates. Let the vehicle flight azimuth, $a$, be measured in degrees clockwise from true north, then the five statistical parameters with respect to the flight axes are given by the following equations:

(a) The means

$$\overline{X}_a = \overline{U} \sin a + \overline{V} \cos a \ , \tag{2.27}$$

$$\overline{Y}_a = \overline{V} \sin a - \overline{U} \cos a \ . \tag{2.28}$$

(b) The variances

$$S^2_{x\,a} = S^2_u \sin^2 a + S^2_v \cos^2 \cos^2 a \ + 2R(U,V) S_U S_V \sin a \ \cos a \ , \tag{2.29}$$

$$S^2_{y\,a} = S^2_v \sin^2 a + S^2_u \cos^2 \cos^2 a \ - 2R(U,V) S_U S_V \sin a \ \cos a \ . \tag{2.30}$$

(c) The correlation coefficients

$$R(x,y)_a = \frac{COV(x,y)_a}{S_{x\,a}\, S_{y\,a}} \ , \tag{2.31}$$

where cov $(X,Y)_a$ is the rotated covariance

$$COV(x,y)_a = R(U,V)\, S_u S_v \ (\sin^2 a - \cos^2 a) + \sin a \ \cos a \ (S^2_v - S^2_u) \ . \tag{2.32}$$

TABLE 2-54. KSC Bivariate Normal Wind Statistics, 90º Flight Azimuth.

February

| Alt (km) | $\bar{u}$ | $\bar{v}$ | $S(u)$ | $S(v)$ | $R(uv)$ | $N$ |
|---|---|---|---|---|---|---|
| 0 | 0.65 | –0.21 | 3.28 | 3.68 | –0.2615 | 1,074 |
| 1 | 3.70 | 1.62 | 7.17 | 6.80 | –0.0277 | 1,074 |
| 2 | 7.88 | 1.48 | 7.74 | 6.82 | 0.0083 | 1,074 |
| 3 | 11.70 | 1.68 | 8.20 | 7.40 | 0.0437 | 1,074 |
| 4 | 15.21 | 2.10 | 9.11 | 8.10 | 0.0338 | 1,074 |
| 5 | 18.97 | 2.49 | 10.16 | 8.98 | 0.0501 | 1,074 |
| 6 | 22.95 | 2.98 | 11.14 | 9.62 | 0.1124 | 1,074 |
| 7 | 26.58 | 3.31 | 12.43 | 10.48 | 0.1653 | 1,074 |
| 8 | 30.23 | 3.40 | 13.80 | 11.54 | 0.1991 | 1,074 |
| 9 | 34.26 | 3.50 | 15.38 | 12.64 | 0.2148 | 1,074 |
| 10 | 38.18 | 3.39 | 16.45 | 13.89 | 0.2159 | 1,074 |
| 11 | 42.13 | 3.32 | 17.08 | 14.91 | 0.2281 | 1,074 |
| 12 | 44.84 | 3.49 | 16.53 | 14.56 | 0.2267 | 1,074 |
| 13 | 44.76 | 3.52 | 15.06 | 12.85 | 0.2863 | 1,074 |
| 14 | 41.65 | 3.33 | 13.08 | 11.05 | 0.2759 | 1,074 |
| 15 | 36.73 | 2.90 | 11.45 | 9.28 | 0.2060 | 1,074 |
| 16 | 31.59 | 2.60 | 10.27 | 8.25 | 0.1485 | 1,074 |
| 17 | 25.36 | 1.94 | 9.20 | 7.04 | 0.1429 | 1,074 |
| 18 | 18.78 | 1.41 | 8.49 | 5.67 | 0.2378 | 1,074 |
| 19 | 12.77 | 0.99 | 7.84 | 4.52 | 0.2280 | 1,074 |
| 20 | 7.85 | 0.63 | 7.40 | 3.89 | 0.2540 | 1,074 |
| 21 | 5.21 | 0.18 | 7.26 | 4.23 | 0.2321 | 1,074 |
| 22 | 4.04 | –0.14 | 7.66 | 4.11 | 0.2344 | 1,074 |
| 23 | 3.47 | –0.02 | 7.87 | 4.10 | 0.2736 | 1,074 |
| 24 | 3.65 | 0.09 | 8.27 | 3.89 | 0.2797 | 1,074 |
| 25 | 3.88 | –0.02 | 9.15 | 3.85 | 0.3470 | 1,074 |
| 26 | 4.48 | 0.11 | 9.82 | 4.09 | 0.3075 | 1,074 |
| 27 | 5.14 | 0.35 | 10.57 | 4.13 | 0.2299 | 1,074 |
| 28 | 9.08 | 3.22 | 9.48 | 4.85 | 0.2951 | 79 |
| 29 | 10.78 | 3.67 | 9.42 | 5.67 | 0.2540 | 79 |
| 30 | 12.53 | 4.18 | 9.91 | 6.03 | 0.3252 | 77 |
| 31 | 14.63 | 4.15 | 10.65 | 6.80 | 0.3548 | 81 |
| 32 | 16.83 | 3.73 | 11.72 | 6.39 | 0.3957 | 81 |
| 33 | 18.41 | 2.85 | 12.90 | 6.36 | 0.3947 | 81 |
| 34 | 18.41 | 1.51 | 13.55 | 6.31 | 0.3675 | 81 |
| 35 | 17.61 | 0.38 | 14.31 | 6.10 | 0.3274 | 85 |
| 36 | 16.64 | –0.96 | 14.59 | 6.74 | 0.2480 | 85 |
| 37 | 15.13 | –0.45 | 15.13 | 7.87 | 0.2802 | 87 |
| 38 | 14.47 | 0.23 | 15.83 | 7.59 | 0.2648 | 87 |
| 39 | 13.94 | 0.18 | 16.79 | 8.00 | 0.1863 | 88 |
| 40 | 12.71 | 0.94 | 18.33 | 8.39 | 0.1776 | 87 |
| 41 | 11.60 | 2.74 | 18.69 | 7.60 | 0.0952 | 88 |
| 42 | 11.82 | 3.63 | 18.82 | 7.55 | 0.0531 | 89 |
| 43 | 13.25 | 5.08 | 18.76 | 8.96 | 0.1419 | 89 |
| 44 | 13.86 | 5.74 | 18.75 | 9.34 | 0.1513 | 86 |
| 45 | 14.87 | 6.27 | 19.63 | 10.11 | 0.1188 | 88 |
| 46 | 16.49 | 7.30 | 20.52 | 10.88 | 0.1161 | 90 |
| 47 | 18.46 | 8.75 | 20.73 | 10.76 | 0.0906 | 89 |
| 48 | 18.87 | 8.83 | 21.28 | 11.22 | 0.0649 | 89 |
| 49 | 19.98 | 9.23 | 21.02 | 11.23 | 0.0061 | 88 |
| 50 | 21.35 | 8.57 | 21.48 | 12.30 | 0.0203 | 88 |
| 51 | 22.91 | 9.72 | 21.19 | 12.61 | 0.1194 | 85 |
| 52 | 25.42 | 9.51 | 21.33 | 12.36 | 0.0854 | 84 |
| 53 | 28.18 | 9.16 | 20.59 | 12.27 | 0.1107 | 82 |
| 54 | 30.62 | 8.99 | 19.63 | 13.02 | 0.1702 | 82 |
| 55 | 34.27 | 11.12 | 18.00 | 13.33 | 0.1582 | 82 |
| 56 | 38.00 | 12.25 | 18.41 | 13.41 | 0.1751 | 80 |
| 57 | 41.51 | 13.97 | 18.57 | 12.58 | 0.1623 | 79 |
| 58 | 45.58 | 15.42 | 17.90 | 11.80 | 0.2153 | 66 |
| 59 | 48.06 | 16.24 | 18.17 | 12.11 | 0.2007 | 63 |
| 60 | 49.71 | 15.19 | 18.69 | 12.01 | 0.0992 | 59 |
| 61 | 54.11 | 14.82 | 18.05 | 11.80 | 0.2973 | 44 |
| 62 | 57.30 | 13.09 | 19.38 | 11.85 | 0.2644 | 33 |
| 63 | 58.44 | 10.28 | 18.68 | 11.33 | –0.0387 | 32 |
| 64 | 60.36 | 6.82 | 15.37 | 10.89 | –0.0402 | 28 |
| 65 | 59.89 | 3.50 | 15.01 | 11.49 | 0.0436 | 28 |
| 66 | 60.07 | –0.26 | 15.83 | 12.08 | –0.0695 | 27 |
| 67 | 60.64 | –5.68 | 15.12 | 13.12 | –0.2037 | 25 |
| 68 | 59.52 | –5.70 | 16.42 | 9.90 | –0.0087 | 23 |
| 69 | 56.48 | –8.22 | 16.75 | 11.44 | 0.1063 | 23 |
| 70 | 50.52 | –12.81 | 18.49 | 13.25 | 0.0056 | 21 |
| 71 | 42.76 | –14.81 | 19.21 | 13.63 | 0.1244 | 21 |

## TABLE 2-54 - February (Continued)

| Alt (km) | $\bar{u}$ | $\bar{v}$ | $S(u)$ | $S(v)$ | $R(uv)$ | $N$ |
|---|---|---|---|---|---|---|
| 72 | 37.11 | –15.58 | 20.49 | 13.01 | 0.3917 | 19 |
| 73 | 30.11 | –11.11 | 21.77 | 12.79 | 0.4381 | 19 |
| 74 | 24.20 | –8.55 | 23.75 | 13.37 | 0.1233 | 20 |
| 75 | 19.25 | –5.70 | 22.79 | 16.99 | –0.0194 | 20 |
| 76 | 13.78 | –0.28 | 21.72 | 19.80 | 0.1905 | 18 |
| 77 | 11.94 | 5.87 | 20.09 | 22.48 | 0.2601 | 16 |
| 78 | 8.31 | 10.81 | 20.44 | 23.17 | 0.3862 | 16 |
| 79 | 6.75 | 15.69 | 20.60 | 22.81 | 0.4347 | 16 |
| 80 | 6.37 | 18.87 | 20.72 | 22.49 | 0.4223 | 16 |
| 81 | 5.81 | 21.56 | 21.39 | 22.65 | 0.3534 | 16 |
| 82 | 5.37 | 23.12 | 22.95 | 23.44 | 0.2424 | 16 |
| 83 | 6.53 | 26.47 | 25.31 | 22.52 | 0.0293 | 15 |
| 84 | 4.93 | 25.43 | 29.40 | 25.08 | –0.0659 | 14 |
| 85 | 5.27 | 30.00 | 38.65 | 27.99 | –0.1226 | 11 |
| 86 | 8.20 | 25.20 | 12.45 | 27.20 | 0.8446 | 5 |

## TABLE 2-55. KSC Bivariate Normal Wind Statistics, 90º Flight Azimuth.

### July

| Alt (km) | $\bar{u}$ | $\bar{v}$ | $S(u)$ | $S(v)$ | $R(uv)$ | $N$ |
|---|---|---|---|---|---|---|
| 0 | –0.54 | 1.53 | 2.29 | 1.96 | –0.1370 | 1,178 |
| 1 | 0.63 | 2.74 | 4.34 | 3.35 | –0.0144 | 1,178 |
| 2 | 0.95 | 1.94 | 4.43 | 3.54 | 0.0654 | 1,178 |
| 3 | 1.12 | 1.63 | 4.61 | 3.54 | 0.0995 | 1,178 |
| 4 | 1.11 | 1.42 | 4.81 | 3.79 | 0.0843 | 1,178 |
| 5 | 0.88 | 1.08 | 4.92 | 3.95 | 0.0510 | 1,178 |
| 6 | 0.52 | 0.77 | 4.95 | 4.17 | 0.0431 | 1,178 |
| 7 | 0.02 | 0.39 | 5.02 | 4.35 | 0.0935 | 1,178 |
| 8 | –0.34 | –0.13 | 5.50 | 4.74 | 0.1759 | 1,178 |
| 9 | –0.82 | –0.71 | 6.38 | 5.46 | 0.2705 | 1,178 |
| 10 | –1.19 | –1.31 | 7.35 | 6.28 | 0.3098 | 1,178 |
| 11 | –1.70 | –2.01 | 8.66 | 7.05 | 0.3235 | 1,178 |
| 12 | –2.30 | –2.95 | 9.77 | 7.64 | 0.3190 | 1,178 |
| 13 | –3.01 | –4.08 | 10.30 | 7.92 | 0.2831 | 1,178 |
| 14 | –3.55 | –4.57 | 9.09 | 7.21 | 0.2509 | 1,178 |
| 15 | –4.26 | –3.86 | 6.75 | 5.63 | 0.2748 | 1,178 |
| 16 | –4.86 | –2.63 | 4.93 | 4.16 | 0.3044 | 1,178 |
| 17 | –6.00 | –1.76 | 3.73 | 3.35 | 0.2364 | 1,178 |
| 18 | –8.10 | –1.21 | 3.16 | 2.97 | 0.0879 | 1,178 |
| 19 | –10.44 | –0.99 | 3.05 | 2.71 | 0.1215 | 1,178 |
| 20 | –12.88 | –0.89 | 3.50 | 2.59 | 0.0010 | 1,178 |
| 21 | –14.97 | –0.54 | 3.50 | 2.90 | –0.2085 | 1,178 |
| 22 | –16.50 | –0.24 | 3.32 | 3.35 | –0.1356 | 1,178 |
| 23 | –17.60 | –0.08 | 3.38 | 3.24 | –0.0129 | 1,178 |
| 24 | –18.62 | –0.14 | 3.56 | 2.98 | –0.0581 | 1,178 |
| 25 | –19.34 | –0.44 | 3.91 | 2.94 | –0.0430 | 1,178 |
| 26 | –20.00 | –0.49 | 4.41 | 3.21 | –0.1577 | 1,178 |
| 27 | –20.41 | –0.61 | 4.64 | 3.54 | –0.1129 | 1,178 |
| 28 | –22.01 | –1.11 | 3.21 | 2.62 | 0.1234 | 97 |
| 29 | –23.34 | –0.83 | 3.35 | 2.80 | 0.0700 | 95 |
| 30 | –24.78 | –0.07 | 3.75 | 3.06 | 0.2547 | 96 |
| 31 | –25.64 | 1.09 | 4.46 | 3.13 | 0.0244 | 99 |
| 32 | –26.25 | 1.56 | 4.63 | 3.56 | –0.0625 | 99 |
| 33 | –26.40 | 1.13 | 5.10 | 3.71 | –0.0094 | 100 |
| 34 | –27.03 | 0.61 | 5.16 | 3.34 | –0.0764 | 99 |
| 35 | –28.10 | 0.48 | 4.86 | 3.77 | –0.1564 | 99 |
| 36 | –29.21 | 0.19 | 4.61 | 3.74 | –0.0919 | 101 |
| 37 | –30.91 | 0.24 | 5.24 | 4.29 | –0.0018 | 100 |
| 38 | –32.28 | 0.35 | 5.46 | 4.70 | 0.0628 | 102 |
| 39 | –34.15 | 0.14 | 5.24 | 4.78 | –0.0275 | 104 |
| 40 | –35.96 | 0.04 | 5.23 | 4.90 | –0.0682 | 103 |
| 41 | –37.69 | –0.82 | 5.82 | 5.08 | –0.0481 | 104 |
| 42 | –39.93 | –1.75 | 6.07 | 5.81 | –0.1918 | 106 |
| 43 | –43.22 | –1.40 | 6.20 | 6.16 | –0.1917 | 104 |
| 44 | –46.58 | –0.18 | 5.80 | 6.99 | –0.0695 | 106 |
| 45 | –48.60 | 1.66 | 6.34 | 7.60 | 0.1183 | 107 |
| 46 | –49.14 | 3.22 | 7.69 | 7.65 | 0.2902 | 106 |
| 47 | –50.39 | 3.88 | 7.85 | 6.69 | 0.2375 | 106 |
| 48 | –51.40 | 4.10 | 8.54 | 6.59 | 0.2990 | 105 |
| 49 | –51.35 | 4.54 | 8.57 | 6.30 | 0.0453 | 105 |

## Table 2-55 - July (Continued)

| Alt (km) | $\bar{u}$ | $\bar{v}$ | $S(u)$ | $S(v)$ | $R(uv)$ | $N$ |
|---|---|---|---|---|---|---|
| 50 | −52.11 | 4.93 | 8.52 | 7.40 | −0.0417 | 104 |
| 51 | −52.91 | 4.97 | 8.58 | 7.71 | −0.0531 | 103 |
| 52 | −54.59 | 5.62 | 8.19 | 7.92 | −0.0735 | 101 |
| 53 | −54.51 | 5.67 | 9.09 | 9.44 | −0.1176 | 100 |
| 54 | −54.17 | 6.33 | 9.78 | 10.84 | 0.0299 | 101 |
| 55 | −53.70 | 6.03 | 10.47 | 11.50 | 0.2275 | 94 |
| 56 | −51.89 | 5.62 | 11.76 | 11.45 | 0.2552 | 93 |
| 57 | −51.29 | 4.13 | 12.65 | 11.21 | 0.2054 | 87 |
| 58 | −49.30 | 3.92 | 14.23 | 12.04 | 0.1667 | 79 |
| 59 | −47.97 | 3.76 | 15.15 | 12.32 | 0.0217 | 71 |
| 60 | −46.13 | 4.98 | 16.16 | 13.47 | 0.0904 | 62 |
| 61 | −45.33 | 4.16 | 20.90 | 16.18 | 0.2517 | 43 |
| 62 | −42.28 | 5.19 | 24.50 | 17.57 | 0.3672 | 36 |
| 63 | −37.80 | 4.30 | 29.76 | 17.32 | 0.3026 | 30 |
| 64 | −35.70 | 5.09 | 32.20 | 18.25 | 0.2689 | 23 |
| 65 | −35.62 | 6.04 | 31.20 | 18.07 | 0.2073 | 26 |
| 66 | −35.35 | 6.57 | 30.59 | 20.24 | 0.2556 | 23 |
| 67 | −38.45 | 13.15 | 33.24 | 21.67 | 0.0476 | 20 |
| 68 | −32.53 | 14.26 | 27.37 | 21.18 | −0.0163 | 19 |
| 69 | −28.16 | 6.16 | 26.24 | 22.93 | −0.0761 | 19 |
| 70 | −20.50 | −1.28 | 23.73 | 20.55 | −0.1924 | 18 |
| 71 | −22.65 | −5.71 | 21.02 | 18.05 | −0.2565 | 17 |
| 72 | −21.44 | −12.37 | 21.69 | 21.78 | −0.3460 | 16 |
| 73 | −22.20 | −20.33 | 23.45 | 24.42 | −0.4228 | 15 |
| 74 | −29.58 | −18.17 | 17.93 | 25.34 | −0.2819 | 12 |
| 75 | −25.73 | −22.73 | 20.10 | 29.03 | −0.3982 | 11 |
| 76 | −22.60 | −24.40 | 21.90 | 29.47 | −0.4009 | 10 |
| 77 | −20.00 | −24.00 | 23.75 | 30.51 | −0.4689 | 9 |
| 78 | −12.30 | −20.70 | 27.19 | 29.59 | −0.3069 | 10 |
| 79 | −12.10 | −23.90 | 24.32 | 27.73 | −0.6421 | 10 |
| 80 | −8.20 | −24.40 | 24.75 | 27.89 | −0.7128 | 10 |
| 81 | −5.40 | −24.90 | 24.34 | 28.76 | −0.7349 | 10 |
| 82 | −1.60 | −24.40 | 23.39 | 28.79 | −0.7536 | 10 |
| 83 | 0.89 | −21.22 | 23.13 | 29.65 | −0.7295 | 9 |
| 84 | 4.44 | −18.67 | 20.62 | 29.10 | −0.6736 | 9 |
| 85 | 8.11 | −15.67 | 17.69 | 28.62 | −0.5784 | 9 |
| 86 | 11.17 | −17.67 | 13.99 | 27.32 | 0.0452 | 6 |
| 87 | 13.25 | −23.25 | 14.10 | 19.49 | 0.0066 | 4 |
| 88 | 12.50 | −7.75 | 10.92 | 20.35 | −0.5731 | 4 |
| 89 | 11.25 | 1.00 | 11.01 | 22.05 | −0.6428 | 4 |
| 90 | 8.67 | 17.33 | 14.61 | 25.10 | −0.5821 | 3 |

## TABLE 2-56. VAFB Bivariate Normal Wind Statistics, 90º Flight Azimuth.

### December

| Alt (km) | $\bar{u}$ | $\bar{v}$ | $S(u)$ | $S(v)$ | $R(uv)$ | $N$ |
|---|---|---|---|---|---|---|
| 0 | 0.42 | −1.10 | 2.83 | 3.19 | −0.4912 | 620 |
| 1 | 1.26 | −2.66 | 4.47 | 7.29 | −0.0611 | 620 |
| 2 | 3.84 | −3.63 | 5.80 | 8.50 | 0.0404 | 620 |
| 3 | 6.77 | −4.34 | 7.54 | 9.85 | 0.0973 | 620 |
| 4 | 9.62 | −4.95 | 9.38 | 11.60 | 0.1032 | 620 |
| 5 | 12.03 | −5.36 | 10.96 | 13.02 | 0.1663 | 620 |
| 6 | 14.15 | −5.89 | 12.39 | 14.87 | 0.2362 | 620 |
| 7 | 16.21 | −6.43 | 14.05 | 16.83 | 0.3037 | 620 |
| 8 | 18.23 | −6.67 | 15.60 | 18.32 | 0.3539 | 620 |
| 9 | 20.20 | −7.09 | 16.77 | 19.84 | 0.3781 | 620 |
| 10 | 22.04 | −7.14 | 17.47 | 20.94 | 0.4048 | 620 |
| 11 | 23.47 | −6.98 | 17.02 | 20.60 | 0.3873 | 620 |
| 12 | 24.04 | −6.00 | 15.52 | 18.85 | 0.3938 | 620 |
| 13 | 23.41 | −4.83 | 13.90 | 16.23 | 0.3869 | 620 |
| 14 | 21.68 | −3.76 | 11.78 | 13.94 | 0.3941 | 620 |
| 15 | 19.36 | −3.13 | 10.00 | 11.72 | 0.4016 | 620 |
| 16 | 16.25 | −2.72 | 8.84 | 9.77 | 0.4085 | 620 |
| 17 | 13.07 | −2.31 | 7.83 | 8.26 | 0.4364 | 620 |
| 18 | 9.49 | −2.23 | 6.71 | 6.35 | 0.4716 | 620 |
| 19 | 6.20 | −2.34 | 6.07 | 4.95 | 0.4525 | 620 |
| 20 | 3.93 | −2.50 | 5.97 | 4.26 | 0.3638 | 620 |
| 21 | 1.91 | −2.66 | 5.99 | 3.95 | 0.2496 | 620 |
| 22 | 0.37 | −2.53 | 6.41 | 3.80 | 0.2832 | 620 |
| 23 | −0.40 | −2.48 | 7.23 | 3.59 | 0.2116 | 620 |
| 24 | −0.57 | −2.73 | 7.77 | 3.50 | 0.1918 | 620 |

# TABLE 2-56 - December (Continued)

| Alt (km) | $\bar{u}$ | $\bar{v}$ | $S(u)$ | $S(v)$ | $R(uv)$ | $N$ |
|---|---|---|---|---|---|---|
| 25 | –0.84 | –2.52 | 8.63 | 3.53 | 0.2330 | 620 |
| 26 | –0.56 | –2.49 | 9.99 | 3.96 | 0.2718 | 620 |
| 27 | 0.38 | –2.67 | 11.78 | 4.53 | 0.3282 | 620 |
| 28 | 0.17 | –3.03 | 13.65 | 4.04 | 0.3967 | 106 |
| 29 | 2.03 | –3.18 | 15.22 | 4.78 | 0.5140 | 108 |
| 30 | 4.52 | –3.20 | 17.05 | 5.48 | 0.5903 | 113 |
| 31 | 6.86 | –3.19 | 18.71 | 6.40 | 0.6286 | 111 |
| 32 | 9.51 | –2.79 | 20.17 | 7.01 | 0.6830 | 110 |
| 33 | 14.00 | –2.26 | 22.75 | 7.86 | 0.7448 | 112 |
| 34 | 18.29 | –1.53 | 24.38 | 8.75 | 0.7516 | 113 |
| 35 | 22.04 | –0.89 | 25.28 | 9.45 | 0.7375 | 112 |
| 36 | 26.55 | –0.22 | 26.22 | 10.17 | 0.7641 | 113 |
| 37 | 31.68 | 0.12 | 27.04 | 10.67 | 0.7702 | 112 |
| 38 | 36.19 | 0.03 | 27.37 | 11.06 | 0.7547 | 114 |
| 39 | 39.77 | –0.34 | 27.19 | 11.28 | 0.7617 | 111 |
| 40 | 42.83 | 0.17 | 27.23 | 11.77 | 0.7349 | 114 |
| 41 | 45.87 | 1.35 | 27.99 | 13.06 | 0.6655 | 110 |
| 42 | 48.88 | 3.02 | 28.51 | 14.11 | 0.5957 | 110 |
| 43 | 53.18 | 4.46 | 29.04 | 14.46 | 0.5164 | 111 |
| 44 | 57.08 | 6.14 | 28.86 | 14.90 | 0.4416 | 112 |
| 45 | 60.79 | 7.65 | 28.65 | 15.63 | 0.3723 | 110 |
| 46 | 63.97 | 9.41 | 28.87 | 16.39 | 0.3035 | 111 |
| 47 | 67.35 | 11.59 | 28.74 | 16.41 | 0.3110 | 113 |
| 48 | 70.04 | 13.00 | 28.86 | 16.97 | 0.2797 | 112 |
| 49 | 72.05 | 14.28 | 28.58 | 17.59 | 0.2734 | 109 |
| 50 | 73.92 | 14.67 | 29.24 | 18.60 | 0.2191 | 106 |
| 51 | 75.08 | 14.23 | 29.00 | 17.95 | 0.1898 | 108 |
| 52 | 76.38 | 15.02 | 29.36 | 18.01 | 0.1559 | 108 |
| 53 | 77.19 | 14.67 | 29.87 | 17.75 | 0.1501 | 106 |
| 54 | 77.14 | 14.57 | 29.66 | 17.38 | 0.1622 | 106 |
| 55 | 78.67 | 13.91 | 29.99 | 16.80 | 0.0698 | 103 |
| 56 | 78.75 | 11.93 | 30.38 | 18.05 | 0.0278 | 99 |
| 57 | 78.57 | 10.00 | 29.99 | 19.05 | 0.0012 | 93 |
| 58 | 78.51 | 12.06 | 30.49 | 21.88 | 0.1326 | 89 |
| 59 | 79.89 | 12.51 | 31.18 | 23.15 | 0.1744 | 75 |
| 60 | 76.98 | 10.59 | 34.74 | 23.43 | 0.2544 | 54 |
| 61 | 75.62 | 5.53 | 34.24 | 24.43 | 0.1737 | 32 |
| 62 | 66.76 | –3.38 | 33.96 | 22.77 | 0.0731 | 21 |
| 63 | 69.73 | 6.53 | 33.16 | 18.59 | 0.2412 | 15 |
| 64 | 69.94 | 7.00 | 29.87 | 15.68 | 0.4678 | 16 |
| 65 | 66.13 | 8.40 | 28.03 | 17.35 | 0.7231 | 15 |
| 66 | 64.20 | 7.73 | 28.53 | 18.78 | 0.5116 | 15 |
| 67 | 63.17 | 5.75 | 31.69 | 15.96 | 0.7011 | 12 |
| 68 | 60.85 | 4.92 | 32.18 | 18.40 | 0.3654 | 13 |
| 69 | 61.93 | 0.00 | 32.28 | 17.72 | 0.3567 | 14 |
| 70 | 60.92 | 2.00 | 34.46 | 13.97 | 0.6552 | 12 |
| 71 | 57.08 | –1.38 | 32.15 | 20.62 | 0.5138 | 13 |
| 72 | 53.92 | 0.46 | 30.98 | 22.33 | 0.4664 | 13 |
| 73 | 56.09 | 4.91 | 28.16 | 23.85 | 0.2784 | 11 |
| 74 | 54.73 | 7.09 | 24.92 | 24.54 | 0.2137 | 11 |
| 75 | 54.20 | 9.80 | 22.30 | 26.00 | 0.2352 | 10 |
| 76 | 51.80 | 10.10 | 18.37 | 25.87 | 0.3741 | 10 |
| 77 | 49.60 | 9.20 | 15.42 | 25.25 | 0.5487 | 10 |
| 78 | 47.00 | 7.50 | 14.23 | 24.24 | 0.6515 | 10 |
| 79 | 44.10 | 5.90 | 15.29 | 22.78 | 0.5755 | 10 |
| 80 | 41.30 | 2.70 | 18.23 | 21.28 | 0.3401 | 10 |
| 81 | 38.30 | –0.20 | 21.45 | 20.40 | 0.0525 | 10 |
| 82 | 34.90 | –3.50 | 24.28 | 20.59 | –0.2082 | 10 |
| 83 | 33.56 | –4.00 | 27.43 | 22.22 | –0.5057 | 9 |
| 84 | 29.89 | –7.78 | 28.92 | 26.07 | –0.5441 | 9 |
| 85 | 26.67 | –11.44 | 28.56 | 29.41 | –0.5107 | 9 |
| 86 | 15.33 | –26.67 | 33.48 | 36.75 | –0.5011 | 3 |

TABLE 2-57. VAFB Bivariate Normal Wind Statistics, 90° Flight Azimuth.

July

| Alt (km) | $\bar{u}$ | $\bar{v}$ | $S(u)$ | $S(v)$ | $R(uv)$ | $N$ |
|---|---|---|---|---|---|---|
| 0 | 2.03 | –1.61 | 1.93 | 1.82 | –0.4607 | 620 |
| 1 | 0.25 | –1.90 | 2.54 | 3.87 | –0.2064 | 620 |
| 2 | –0.25 | –0.16 | 3.04 | 3.92 | –0.1869 | 620 |
| 3 | 0.88 | 1.60 | 4.03 | 4.32 | –0.1257 | 620 |
| 4 | 1.76 | 2.82 | 4.86 | 4.66 | 0.0035 | 620 |
| 5 | 2.26 | 3.40 | 5.46 | 4.83 | 0.0642 | 620 |
| 6 | 2.90 | 3.94 | 6.24 | 5.29 | 0.0861 | 620 |
| 7 | 3.83 | 4.72 | 6.98 | 6.08 | 0.0503 | 620 |
| 8 | 5.03 | 5.86 | 7.90 | 6.95 | 0.0402 | 620 |
| 9 | 6.17 | 7.29 | 8.72 | 7.80 | 0.0001 | 620 |
| 10 | 7.28 | 9.00 | 9.47 | 8.60 | –0.0109 | 620 |
| 11 | 8.53 | 10.92 | 9.98 | 9.35 | –0.0191 | 620 |
| 12 | 9.46 | 12.23 | 9.98 | 9.69 | –0.0163 | 620 |
| 13 | 9.65 | 12.21 | 9.54 | 9.29 | 0.0354 | 620 |
| 14 | 8.59 | 11.05 | 8.47 | 8.28 | 0.1050 | 620 |
| 15 | 6.15 | 8.55 | 7.07 | 6.18 | 0.1610 | 620 |
| 16 | 2.64 | 5.89 | 5.19 | 4.63 | 0.1318 | 620 |
| 17 | –0.71 | 3.89 | 3.93 | 3.57 | 0.2216 | 620 |
| 18 | –3.43 | 2.26 | 3.29 | 2.78 | 0.2395 | 620 |
| 19 | –5.61 | 1.43 | 2.71 | 2.13 | 0.1653 | 620 |
| 20 | –7.34 | 0.85 | 2.49 | 1.99 | 0.1657 | 620 |
| 21 | –9.10 | 0.44 | 2.49 | 1.99 | 0.0821 | 620 |
| 22 | –10.66 | 0.10 | 2.43 | 1.99 | 0.0760 | 620 |
| 23 | –11.96 | –0.12 | 2.54 | 2.00 | 0.0085 | 620 |
| 24 | –13.25 | –0.17 | 2.61 | 2.12 | 0.0240 | 620 |
| 25 | –14.36 | 0.06 | 2.76 | 2.09 | 0.0014 | 620 |
| 26 | –15.11 | 0.25 | 2.88 | 2.11 | 0.0669 | 620 |
| 27 | –15.58 | 0.15 | 3.03 | 2.17 | 0.0456 | 620 |
| 28 | –19.11 | 0.11 | 3.38 | 2.25 | –0.0097 | 94 |
| 29 | –20.29 | 0.04 | 3.38 | 2.48 | –0.0823 | 97 |
| 30 | –21.55 | 0.18 | 3.43 | 2.39 | –0.0422 | 101 |
| 31 | –22.25 | 0.64 | 3.55 | 2.47 | –0.0375 | 104 |
| 32 | –22.84 | 1.23 | 3.68 | 2.70 | –0.2192 | 106 |
| 33 | –23.46 | 1.57 | 3.26 | 2.90 | –0.0749 | 106 |
| 34 | –24.06 | 1.33 | 3.48 | 3.09 | –0.0253 | 107 |
| 35 | –24.90 | 0.79 | 4.18 | 3.30 | 0.0198 | 107 |
| 36 | –26.35 | 1.13 | 4.43 | 3.44 | –0.0830 | 110 |
| 37 | –27.69 | 1.11 | 4.88 | 3.53 | –0.1381 | 108 |
| 38 | –29.02 | 1.17 | 5.07 | 4.25 | –0.1775 | 109 |
| 39 | –30.62 | 0.49 | 4.59 | 3.99 | –0.0286 | 107 |
| 40 | –33.05 | 0.04 | 4.21 | 4.44 | –0.0276 | 108 |
| 41 | –35.54 | –0.23 | 4.34 | 5.07 | 0.0997 | 109 |
| 42 | –37.88 | –0.19 | 4.99 | 5.29 | 0.1510 | 107 |
| 43 | –40.41 | 0.31 | 5.39 | 5.54 | 0.1417 | 109 |
| 44 | –41.96 | 2.01 | 5.52 | 5.87 | 0.0613 | 109 |
| 45 | –43.64 | 3.27 | 5.60 | 5.44 | 0.0489 | 107 |
| 46 | –44.57 | 4.10 | 6.07 | 5.20 | 0.1344 | 108 |
| 47 | –46.00 | 4.44 | 6.75 | 5.71 | 0.1801 | 105 |
| 48 | –47.52 | 4.45 | 6.90 | 6.29 | 0.2254 | 106 |
| 49 | –49.40 | 4.80 | 6.92 | 5.90 | 0.1944 | 107 |
| 50 | –51.39 | 5.17 | 7.59 | 5.63 | 0.2488 | 105 |
| 51 | –53.31 | 5.58 | 8.49 | 6.16 | 0.2050 | 106 |
| 52 | –54.01 | 6.71 | 8.81 | 6.67 | 0.2925 | 100 |
| 53 | –54.54 | 7.59 | 8.93 | 6.89 | 0.1842 | 98 |
| 54 | –54.53 | 7.49 | 9.41 | 7.36 | 0.1331 | 97 |
| 55 | –55.53 | 6.77 | 9.92 | 9.20 | 0.2014 | 91 |
| 56 | –58.55 | 4.79 | 11.25 | 9.96 | 0.1319 | 91 |
| 57 | –60.73 | 2.68 | 11.63 | 11.46 | 0.1282 | 82 |
| 58 | –61.06 | 0.53 | 12.14 | 12.78 | 0.2108 | 72 |
| 59 | –61.69 | 0.70 | 14.06 | 13.00 | 0.1816 | 61 |
| 60 | –62.30 | 2.51 | 16.77 | 14.48 | 0.0693 | 47 |
| 61 | –63.34 | 4.29 | 17.03 | 18.07 | 0.0136 | 38 |
| 62 | –64.82 | 9.15 | 19.55 | 11.57 | 0.1036 | 33 |
| 63 | –61.93 | 8.34 | 20.59 | 11.08 | 0.0527 | 29 |
| 64 | –63.50 | 7.08 | 23.47 | 10.66 | 0.1710 | 26 |
| 65 | –61.59 | 6.41 | 21.56 | 13.39 | 0.0952 | 27 |
| 66 | –52.89 | 8.96 | 20.48 | 13.47 | 0.1283 | 27 |
| 67 | –46.48 | 10.48 | 20.58 | 14.90 | 0.1038 | 25 |
| 68 | –40.27 | 11.82 | 19.36 | 15.72 | 0.0554 | 22 |
| 69 | –32.54 | 11.50 | 19.87 | 18.69 | 0.2531 | 24 |
| 70 | –29.90 | 12.35 | 23.40 | 16.05 | 0.2602 | 20 |
| 71 | –28.60 | 11.05 | 23.10 | 16.57 | 0.0236 | 20 |

TABLE 2-57 - July (Continued)

| Alt (km) | $\bar{u}$ | $\bar{v}$ | $S(u)$ | $S(v)$ | $R(uv)$ | $N$ |
|---|---|---|---|---|---|---|
| 72 | –26.47 | 11.00 | 23.99 | 17.53 | –0.2058 | 19 |
| 73 | –24.11 | 8.89 | 24.28 | 20.22 | –0.4865 | 18 |
| 74 | –22.94 | 7.59 | 24.42 | 25.17 | –0.5938 | 17 |
| 75 | –20.00 | 2.50 | 23.17 | 26.61 | –0.5001 | 16 |
| 76 | –20.06 | –0.13 | 23.21 | 28.44 | –0.4357 | 16 |
| 77 | –20.20 | –2.33 | 24.18 | 29.82 | –0.3646 | 15 |
| 78 | –19.73 | –4.47 | 24.27 | 29.18 | –0.2964 | 15 |
| 79 | –19.13 | –6.13 | 23.86 | 28.03 | –0.2276 | 15 |
| 80 | –17.93 | –7.20 | 22.73 | 26.61 | –0.1851 | 15 |
| 81 | –16.33 | –7.80 | 21.10 | 24.87 | –0.1278 | 15 |
| 82 | –13.93 | –8.13 | 19.00 | 23.38 | –0.0680 | 15 |
| 83 | –10.47 | –7.87 | 16.97 | 22.18 | 0.0175 | 15 |
| 84 | –5.80 | –7.27 | 15.04 | 21.31 | 0.1098 | 15 |
| 85 | –0.07 | –6.20 | 14.07 | 20.86 | 0.2286 | 15 |
| 86 | 6.71 | 7.00 | 12.58 | 23.11 | 0.5795 | 7 |
| 87 | 16.83 | 14.83 | 12.35 | 20.36 | 0.3009 | 6 |
| 88 | 20.50 | 22.00 | 13.61 | 14.54 | 0.3903 | 4 |
| 89 | 21.67 | 25.00 | 9.98 | 15.77 | 0.7796 | 3 |
| 90 | 27.33 | 25.33 | 7.41 | 13.57 | 0.6983 | 3 |

2.3.5.2.2 The Wind Vector Probability Ellipse. Using the meteorological cartesian notation, the probability ellipse that contains $p$-percent of the wind vectors is expressed in the most general form by the conic equation defined by:

$$AX^2+BXY+CY^2+DX+EY+F=0\ . \tag{2.33}$$

where

$A = S_v^2$

$B = -2R(U,V)\, S_u S_v$

$C = S_u^2$

$D = -(B\,\overline{V} + 2\,A\,\overline{U})$

$E = -(B\overline{U} + 2\,C\,\overline{V})$

$F = A(\overline{U})^2 + C\,(\overline{V})^2 + B\overline{U}\,\overline{V} - AC\,\{1-[R(U,V)]^2\}\; l_e^2$

and

$$l_e = \sqrt{-2\,ln(1-P)}\ ,$$

where $P$ is probability.

For convenient usage, values for the lambda parameter to the bivariate normal probability ellipse, $\lambda_e$, and for the bivariate circular normal distribution for selected probabilities are given in Table 2-58. Circular distributions arise when the component standard deviations are equal.

Equation (2.33) is used to derive other functional relationships that describe the properties of the bivariate normal probability ellipse and for graphical displays. The largest and smallest values for *x* and *y* of a given probability ellipse are given by:

$$X_{(w,s)} = \overline{u} \pm S_u \, l_e \; , \qquad (2.34)$$

$$Y_{(w,s)} = \overline{v} \pm S_v \; l_e \; . \qquad (2.35)$$

Using the quadratic equation, solutions for *Y* in equation (2.33) are made by incrementing *X* from $X_S$ to $X_L$ and plotting on a scale that has the same range for *X* and *Y*, as shown in figure 2-18. Such illustrations are helpful in comparing the wind statistics from month to month and between sites. For example, assume that a vehicle trajectory has been wind biased to the monthly mean wind and the flight azimuth is 180º (south) for VAFB, then at 12-km altitude the head and tail quartering wind relative to the monthly mean to the 99-percent probability ellipse would be larger than that for an east launch from KSC, wind biased to the monthly mean.

2.3.5.2.3 The Bivariate Normal Distribution in Polar Coordinates. The bivariate normal probability density function expressed in polar coordinates is used to derive the probability distribution for wind speed given the wind direction, and to express the special relationship for wind vectors relative to the monthly mean wind to an assigned probability ellipse. These relationships are used in the selection of wind vectors to the probability ellipse in subsection 2.3.10 for the synthetic vector wind profile model.

TABLE 2-58. Values Of $l$ For Bivariate Normal Distribution Ellipses And Circles.

| $P$ (Percent) | $l_e$ (ellipse) | $l_c$ (circle) | $P$ (Percent) | $l_e$ (ellipse) | $l_c$ (circle) |
|---|---|---|---|---|---|
| 0.000 | 0.0000 | 0.0000 | 65.000 | 1.4490 | 1.0246 |
| 5.000 | 0.3203 | 0.2265 | 68.268 | 1.5151 | 1.0713 |
| 10.000 | 0.4590 | 0.3246 | 70.000 | 1.5518 | 1.0973 |
| 15.000 | 0.5701 | 0.4031 | 75.000 | 1.6651 | 1.1774 |
| 20.000 | 0.6680 | 0.4723 | 80.000 | 1.7941 | 1.2686 |
| 25.000 | 0.7585 | 0.5363 | 85.000 | 1.9479 | 1.3774 |
| 30.000 | 0.8446 | 0.5972 | 86.466 | 2.0000 | 1.4142 |
| 35.000 | 0.9282 | 0.6563 | 90.000 | 2.1460 | 1.5175 |
| 39.347 | 1.0000 | 0.7071 | 95.000 | 2.4477 | 1.7308 |
| 40.000 | 1.0108 | 0.7147 | 95.450 | 2.4860 | 1.7579 |
| 45.000 | 1.0935 | 0.7732 | 98.000 | 2.7971 | 1.9778 |
| 50.000 | 1.1774 | 0.8325 | 98.168 | 2.8284 | 2.0000 |
| 54.406 | 1.2533 | 0.8862 | 98.889 | 3.0000 | 2.1213 |
| 55.000 | 1.2637 | 0.8936 | 99.000 | 3.0348 | 2.1460 |
| 60.000 | 1.3537 | 0.9572 | 99.730 | 3.4393 | 2.4320 |
| 63.212 | 1.4142 | 1.0000 | 99.9877 | 4.2426 | 3.0000 |

$$l_e = \sqrt{2} \; \sqrt{-1n(1-P)}$$

$$l_c = \sqrt{-1n(1-P)}$$

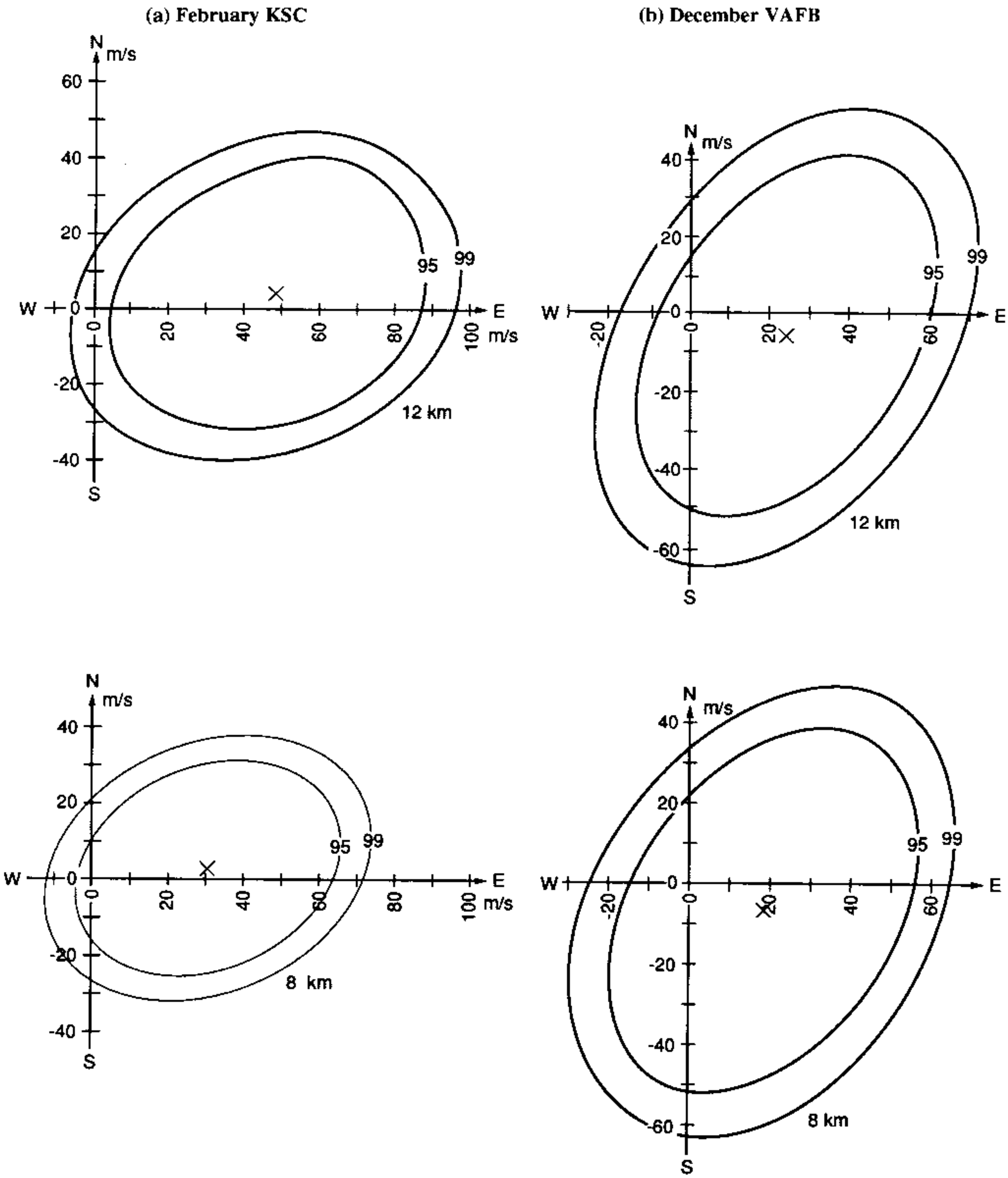



FIGURE 2-18. Comparison Of Wind Vector Probability Ellipses (a) February KSC and (b) December VAFB.

The bivariate normal probability density function in the meteorological polar coordinate system is:*

$$g(r,q) = rd_1\, e^{-1/2\,(a^2r^2 - 2br + c^2)} \;, \tag{2.36}$$

where

$$a^2 = \frac{1}{(1-r^2)}\left[\frac{\sin^2 q}{s_x^2} - \frac{2\rho \cos q \sin q}{s_x s_y} + \frac{\cos^2 q}{s_y^2}\right],$$

$$b = \frac{1}{(1-r^2)}\left[\frac{\bar{x}\sin q}{s_x^2} - \frac{r(\bar{x}\cos q + \bar{y}\sin q)}{s_x s_y} + \frac{\bar{y}\cos q}{s_y^2}\right],$$

$$c^2 = \frac{1}{(1-r^2)}\left[\frac{\bar{x}\sin q}{s_x^2} - \frac{2r\,xy}{s_x s_y} + \frac{\bar{y}^2}{s_y^2}\right],$$

$$d_1 = \frac{1}{2p s_x s_y \sqrt{1-r^2}} \;.$$

$r=\sqrt{x^2+y^2}$ is the modulus of the vector or speed, and $q$ is the direction of the vector. After integrating $g(r,q)$ over $r = 0$ to 8, the probability density function of $q$ is

$$g(q) = \frac{d_1}{a^2} e^{1/2c^2}\left[1 + \sqrt{2p}\left(\frac{b}{a}\right) e^{1/2\left(\frac{b}{a}\right)^2} F\left(\frac{b}{a}\right)\right], \tag{2.37}$$

where $a^2$, $b$, $c^2$, and $d_1$ are as previously defined in equation (2.36) and

$$F\left(\frac{b}{a}\right) = F(x) = \frac{1}{\sqrt{2p}} \int_{-\infty}^{x} e^{-1/2t^2}\, dt \;,$$

is taken from tables of normal distributions or made available through computer subroutines.

If desired, equation (2.37) can be integrated numerically over a chosen range of $q$ to obtain the probability that the vector direction will lie within the chosen range; i.e.,

$$F(q) = \int_{q_2}^{q_1} g(q)\, dq \;. \tag{2.38}$$

One application may be to obtain the probability that the wind flow will be from a given quadrant or sector as, for example, onshore.

* This expression, equation (2.36) (in Smith 1976), is given with respect to the mathematical convention for a vector direction. Not the meteorological convention.

2.3.5.2.4 The Derived Conditional Distribution of Wind Speed Given the Wind Direction (Wind Rose). The conditional probability density function for wind speed, $r$, given a specified value for the wind direction, $q$, can be expressed as

$$f(r|q) = \frac{a^2 r e^{-\frac{1}{2}(a^2 r^2 - b r)}}{1 + \sqrt{2p}\left(\frac{b}{a}\right) e^{\frac{1}{2}\left(\frac{b}{a}\right)^2} F\left(\frac{b}{a}\right)} , \tag{2.39}$$

where the coefficients, $\underline{a}$ and $\underline{b}$ and the function $F\{b/a\}$ are as previously defined in equations (2.33) and (2.37).

From equation (2.39), the mode (most frequent value) of the conditional wind speed given a specified value of the wind direction is the positive solution of the quadratic equation,

$$a^2 b^2 - br - 1 = 0 , \tag{2.40}$$

which is

$$(f|q) = \frac{1}{2a}\left[\left(\frac{b}{a}\right) + \sqrt{4 + \left(\frac{b}{a}\right)^2}\right] . \tag{2.41}$$

The locus of the conditional modal values of wind speed when plotted in polar coordinates versus the given wind directions forms an ellipse.

The noncentral moment for equation (2.39) is expressed as

$$m_n' = \int_0^\infty r^n f(r|q)\, dr . \tag{2.42}$$

Now the first noncentral moment is identical to the first central moment or the expected value, $E(r|q)$. The integration of equation (2.42) for the first moment is sufficiently simple to yield practical computations and can be expressed as

$$E(r|q) = \frac{\left(\frac{b}{a}\right) + \left[1 + \left(\frac{b}{a}\right)^2\right]\sqrt{2p}\; e^{\frac{1}{2}\left(\frac{b}{a}\right)^2} F\left(\frac{b}{a}\right)}{a\left[1 + \left(\frac{b}{a}\right)\sqrt{2p}\; e^{\frac{1}{2}\left(\frac{b}{a}\right)^2} F\left(\frac{b}{a}\right)\right]} . \tag{2.43}$$

Hence, equation (2.43) gives the conditional mean value of the wind speed given a specified value for the wind direction.

The integration of equation (2.39) for the limits $r = 0$ to $r = r^*$ gives the probability that the conditional wind speed is $\leq r^*$ given a value for the wind direction, $q$. This conditional probability distribution function can be written as

$$Pr\{r \leq r^* \mid \theta = \theta_0\} = 1 - \left[\frac{e^{-\frac{1}{2}r_s^2} + \sqrt{2\pi}\left(\frac{b}{a}\right)\{1 - \Phi(r_s)\}}{e^{-\frac{1}{2}\left(\frac{b}{a}\right)^2} + \sqrt{2\pi}\left(\frac{b}{a}\right)\Phi\left\{\frac{b}{a}\right\}}\right] , \tag{2.44}$$

where

$$r_s = \left[ a\, r^* - \left(\frac{b}{a}\right) \right] .$$

By definition, equation (2.44) is an expression for a "wind rose." Empirical wind rose statistics are often tabulated or graphically illustrated giving the frequency that the wind speed is not exceeded for those wind speed values that lie within assigned class intervals of the wind direction. After evaluation of equation (2.41) for various values of wind speed, $r^*$, and the given wind directions, $q$, interpolations can be performed to obtain various percentile values of the conditional wind speed.

For the special case when $\underline{b}$ in equation (2.36) equals zero (i.e., for $\overline{x} = \overline{y} = 0$), the conditional modal values of wind speeds (equation (2.41)), the conditional mean values of wind speeds (equation (2.43)), and the fixed conditional percentile values of wind speeds (interpolated from evaluations of equation (2.44)), when plotted in polar form versus the given wind directions, produce a family of ellipses.

For the special case when $\overline{x} = \overline{y} = 0$, equation (2.39) reduces to the following simple case:

$$Pr\{r ;= r^* | q = q_0\} = 1 - e^{\frac{(-a^2 r^{*2})}{2}} . \qquad (2.45)$$

There is a special significance of equation (2.45) when related to the bivariate normal probability distribution. If $r^*$ and $q$ are measured from the centroid of the probability ellipse, then the probability that $r£\, r^*$ is the same as the given probability ellipse. Further, solving equation (2.45) for $r^*$, gives

$$r^* = \frac{1}{a} \sqrt{-2\, ln(1-P)} \;. \qquad (2.46)$$

If a probability ellipse $P$ is chosen, equation (2.45) gives the distance of $r$ along any $q$ from the centroid of the ellipse to the intercept of the probability ellipse. When computing the wind speed probability for a given $q$ relative to the monthly means, equation (2.46) is applicable.

2.3.5.2.5 Wind Component Statistics. The univariate normal (Gaussian) probability distribution function is used to obtain wind component statistics. In generalized notations, this probability density function is

$$f(t) = \frac{e^{\left(-\frac{1}{2}t^2\right)}}{\sqrt{2p}} , \qquad (2.47)$$

where $t = (X - x)/s_x$ is the standard variate, with $x$ defining the mean and $s_x$ the standard deviation. The cumulative probability distribution function is

$$F(X) = \int_{-\infty}^{X} f(t)\, dt \;. \qquad (2.48)$$

Because this integral cannot be obtained in closed form, it is widely tabulated for zero mean and unit standard deviation. For a convenient reference, selected values of $F(X)$ are given in Table 2-59. To emphasize the connotation of probability, $F(X)$ is shown in Table 2-59 as $P\{X\}$.

TABLE 2-59. Values of *T* For Standardized Normal (Univariate) Distribution for Percentiles and Interpercentile Ranges.

| $t$ | $P(X)$ | $X$ | $P(X_1 \le X \le X_2)$ (%) |
|---|---|---|---|
| –3.0000 | 0.00135 | $\xi - 3.0000\,\sigma$ | 99.73 |
| –2.5758 | 0.00500 | $\xi - 2.5758\,\sigma$ | 99 |
| –2.3263 | 0.01000 | $\xi - 2.3263\,\sigma$ | 98 |
| –2.2410 | 0.0125 | $\xi - 2.2410\,\sigma$ | 97.5 |
| –2.0000 | 0.02275 | $\xi - 2.0000\,\sigma$ | 95.45 |
| –1.9600 | 0.02500 | $\xi - 1.9600\,\sigma$ | 95 |
| –1.6449 | 0.05000 | $\xi - 1.6449\,\sigma$ | 90 |
| –1.2816 | 0.10000 | $\xi - 1.2816\,\sigma$ | 80 |
| –1.0000 | 0.15866 | $\xi - 1.0000\,\sigma$ | 68.268 |
| –0.8416 | 00.2000 | $\xi - 0.8416\,\sigma$ | 60 |
| –0.6745 | 0.25000 | $\xi - 0.6745\,\sigma$ | 50 |
| –0.2533 | 0.40000 | $\xi - 0.2533\,\sigma$ | 20 |
| 0.0000 | 0.50000 | $\xi$ | |
| 0.2533 | 0.60000 | $\xi + 0.2533\,\sigma$ | |
| 0.6745 | 0.75000 | $\xi + 0.6745\,\sigma$ | |
| 0.8416 | 0.80000 | $\xi + 0.8614\,\sigma$ | |
| 1.0000 | 0.84134 | $\xi + 1.0000\,\sigma$ | |
| 1.2816 | 0.90000 | $\xi + 1.2816\,\sigma$ | |
| 1.6449 | 0.95000 | $\xi + 1.6449\,\sigma$ | |
| 1.9600 | 0.97500 | $\xi + 1.9600\,\sigma$ | |
| 2.0000 | 0.97725 | $\xi + 2.0000\,\sigma$ | |
| 2.2410 | 0.9875 | $\xi + 2.2410\,\sigma$ | |
| 2.3263 | 0.99000 | $\xi + 2.3263\,\sigma$ | |
| 2.5758 | 0.99500 | $\xi + 2.5758\,\sigma$ | |
| 3.0000 | 0.99865 | $\xi + 3.0000\,\sigma$ | |

where $X_1 = \xi - t\sigma$ and $X_2 = \xi + t\sigma$

The $t$ values in Table 2-59 are used as multiplier factors to the standard deviation to express the probability that a normally distributed variable, $X$, is less than or equal to a given value as

$$P\{X \leq \text{mean} + ts_x\} = \text{probability, } p \quad . \tag{2.49}$$

For example, when $t$ = 1.6449, the probability that $X$ is less than or equal to the mean plus 1.6449 standard deviations is called the 95th percentile value of $X$. Also given in Table 2-59 are the numerical values to express the probability that $X$ falls in the interval $X_1$ to $X_2$; i.e.,

$$P\{X_1 \leq X \leq X_2\} = \text{Interpercentile Range} \quad , \tag{2.50}$$

where

$$X_1 = \overline{X} - ts_x$$

$$X_2 = \overline{X} + ts_x \; .$$

For $t$ = 1.9602 the probability that $X$ lies in the interval $X_1$ to $X_2$ is 0.95. The values of $X_1$ and $X_2$ in this example comprise the 95th interpercentile range.

For a normally distributed variable, the mode (most frequent value) and the median (50th percentile) are the same as the mean value. The means and standard deviations of wind components are used in equations (2.49) and (2.50) to compute the percentile values and interpercentile ranges of the $U$ and $V$ wind components. Equation (2.49) is a straight line on a normal probability graph.

To obtain the wind component statistics with respect to orthogonal coordinate axes other than zonal and meridional, one should use the coordinate rotation equations (2.27) through (2.32).

2.3.5.2.6 Envelope of Wind Profiles Versus an Envelope of Percentiles. It is a usual practice to plot the points versus altitude for the interpercentile range for wind components (e.g., $u \pm ts_u$) at discrete altitudes and to connect these points. This convenient display can be misinterpreted. Since the winds are not perfectly correlated between all altitude levels, then the envelope of percentile values, for example the 95th interpercentile range ($u \pm 1.96s_u$), the percentage of wind profiles would lie on the interpercentile bounds over all altitudes. The interlevel wind correlations decrease as the altitude interval increases. Suppose that there are five independent wind altitude levels between 0- and 12-km altitude. Then the percentage of wind profiles that lie within the bounds of the 95-interpercentile range is only 77.4 percent. This is obtained by $(0.95)^5 = 0.7737$. For five independent wind levels, the required interpercentile range taken at discrete altitudes to envelop 95 percent of the wind profiles is 98.98th interpercentile range, $(0.95)^{1/5} = 0.9898$. The percentage of wind profiles that lie within the 95-percent probability ellipses at 1-km intervals from 3- to 16-km altitude from a 12-year period of wind records for KSC approximates this example. The percentage of wind profiles for KSC, April, that lie within the 95th percent wind ellipses taken at 1-km intervals versus altitude is illustrated in figure 2-19. An aerospace vehicle should be designed to fly through a certain percent of the wind profiles by monthly reference periods, not just an assigned percent of the wind vectors at discrete altitudes. This raises the issue: What size should the wind vector probability ellipses at discrete altitudes be for aerospace vehicle design? This analysis suggests that the monthly 99-percent probability ellipses at discrete altitudes should be used to envelop 95 percent of the wind profiles over the altitudes of primary interest. This subject is further addressed in section 2.3.10 for synthetic vector wind profile models.

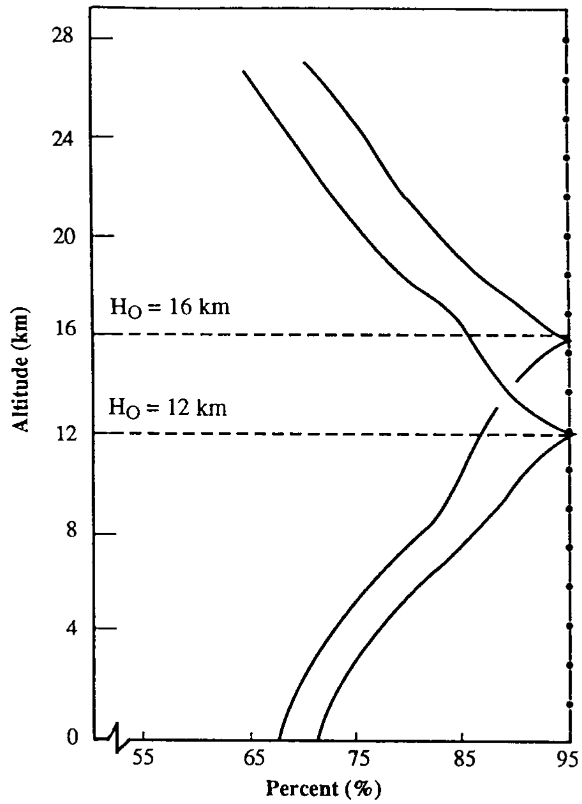



FIGURE 2-19. Percentage Of Wind Profiles (Wind Vectors At 1-Km Intervals) that are Within The 95-Percent Ellipses Versus Altitude, April, KSC.

2.3.5.3 Wind Shear. This subsection presents two wind shear models. They are based on different concepts and methodologies. In section 2.3.5.3.1 a review and presentation of the classical wind speed shear model is presented to contrast with a new wind shear modeling technique given in section 2.3.5.3.2.

2.3.5.3.1 Empirical Wind Shear Model. This is the classical wind speed shear model that has been used with minor modifications for aerospace vehicle design since the early 1960's. It is based on empirical conditional percentile values for wind speed shear for given values for wind speed. Here, wind speed shear is by definition the difference in wind speed between two altitudes divided by the altitude interval. If the altitude interval is specified, then the wind speed change between the two altitudes can be called wind shear for the specified shear interval. Refer to subsection 2.3.6. Historically, two-way empirical frequency distributions for wind speed change for various shear intervals versus wind speed were established by monthly reference periods using rawinsonde data bases for the 99th conditional speed change (or wind speed shear for the specified shear intervals) for given wind speed values. These were established and then enveloped "over" all months to give a "worst" case condition. With the availability of jimsphere wind profile data bases, refinements were made for shear intervals less than 1,000 m. The results are given in Tables 2-64 to 2-73 as wind buildup and back-off wind speed change versus scales of distance (shear interval) and further discussed in section 2.3.6. When applied to the synthetic scalar wind profile model for aerospace vehicle design, the term wind buildup refers to the change in wind speed up to the reference altitude of the given wind speed and wind back-off refers to the change in wind speed for altitudes above the reference altitude. In statistical terms, Tables 2-64 to 2-73 give the 99th conditional wind speed shear for various shear intervals for given wind speed values that envelop all months for each respective site.

2.3.5.3.2 Extreme Value Wind Shear Model. The wind shear model in this subsection has several advantages over the classical empirical wind shear model presented in section 2.3.5.3.1. The technique used to derive this new wind shear model is based on an analytically defined probability function. The procedure is objective. The analytical equations permit generalizations to give consistent comparative results. The empirical wind shear tabulations (Tables 2-64 to 2-73) are for only the 99th conditional percentile value for given wind speeds whereas this new model permits computations for any conditional percentile for wind speed shear given any wind speed.

The extreme, largest wind speed shears for various altitude shear intervals that occurred in the 3- to 16-km altitude layer, for each of 150 per month jimsphere wind profiles, described in subsection 2.3.12.1, were computed. The associated wind speeds for the extreme wind shears were obtained. These data samples were fit by the univariate Gumbel (Ref. 2-56) extreme value probability distribution function. A bivariate extreme value distribution function was used to model the extreme value conditional distribution for wind shear given the wind speed. This wind shear model is used to establish a synthetic wind profile model in section 2.3.10. The bivariate extreme value probability distribution has proven to be a powerful modeling tool for wind shear and for aerospace vehicle ascent structural loads (Ref. 2-52).

There are two forms for the bivariate extreme value probability distribution (Ref. 2-58). They are called the a-case and the m-case. Since the m-case is more general than the a-case; it is used to model the relationship between the extreme largest wind shear and the wind speed. The probability distribution function for the m-case is:

$$F\,(X,Y,m) = \exp\left[-\left(e^{-mX}+e^{-mY}\right)^{\frac{1}{m}}\right] , \qquad (2.51)$$

where

$$-\infty \le X \le \infty$$
$$-\infty \le Y \le \infty$$
$$m \ge 1$$

is a measure of association (correlation) between the two variables.

*X* and *Y* are called the reduced variates; which are defined by:

$$X = \frac{\left(x - m_x\right)}{a_x} , \qquad (2.52)$$

and *x* and *y* are the extreme largest values for the original variates.

$$Y = \frac{\left(y - m_y\right)}{a_y} , \qquad (2.53)$$

Where $m_x, m_y$ is the location parameter or modal value and $a_x, a_y$ is the shape parameter. They are estimated from the sample extremes, means, $(\bar{x}, \bar{y},)$ and standard deviations $(s_X, s_Y)$ using Gumbel's (Ref. 2-56) modified method of moments.

$$\hat{a}_x = \frac{s_x}{s_n} \quad \text{and} \quad \hat{m}_x = \dot{x} - \hat{a}\,\dot{y}_n ,$$

where $s_n$ and $\overline{y}_n$ are the population parameters. They are a function of sample size, $n$. For $n = 150$, $s_n$ = 1.22534, and $\overline{y}_n$ = 0.56461. For large $n \to \infty$, $s_n = \pi/\sqrt{6}$ and $\overline{y}_n$ is Euler's constant, 0.57722.

$$\widehat{m} = \frac{1}{\sqrt{1 - r(x,y)}} \; , \tag{2.54}$$

where for the condition that $m$ is >1, equation (2.51) becomes the product of two independent extreme value distributions which are univariate extreme value probability distribution functions. Some further notations are useful (refs. 2-57 and 2-58).

$$F\,(X,Y;m) = P\{X = X_1, Y \le Y_2; m\} = \int_{-\infty}^{Y}\int_{-\infty}^{X} j\,(X,Y;m)\,dX\,dY \; ,$$

where $j\,(X,Y;m)$ is the probability density function defined by

$$j\,(x,Y;m) = F\,(X,Y;m) * \left[\left(e^{-mX} + e^{-mY}\right)^{\frac{1}{m}-2} e^{(-mX-mY)} \left\{\left(e^{-mX} + e^{-mY}\right)^{\frac{1}{m}} + (m-1)\right\}\right] . \tag{2.55}$$

It is important to note that:

$$F\,(X_\infty,Y;m) = \exp\,(e^{-Y}) \; .$$

These functions are used in deriving the conditional probability distribution function. The interest is to present tables for the conditional percentile values for wind speed shear given class intervals for wind speed. Let $X$ stand for the reduced variate for wind shear and $Y$ stand for the reduced variate for wind speed. The conditional probability distribution function for assigned values for $X$ for given class intervals for $Y$ is:

$$Pr\{X \le X^* | Y_1 \le Y \le Y_2\} = \frac{F\,(X,Y_2;m) - F\,(X^*,Y_1;m)}{F\,(Y_2) - F\,(Y_1)} \; , \tag{2.56}$$

where the denominator, the univariate extreme value probability distribution function for wind speed, is

$$F\,(Y) = \exp\,(-e^{-Y}) \; , \tag{2.57}$$

is evaluated for assigned values for $Y_1$ and $Y_2$. The conditional probability distribution function in terms of the reduced variates is then interpolated for assigned conditional percentile values and then converted into the original extreme value variables using equations (2.52) and (2.53). This is the general method used to establish the conditional percentile shears (Table 2-60) for the assigned class intervals for wind speed. An alternate conditional probability distribution function is:

$$\Pr\{X \le X^* | Y = Y_1\} = Z^{\left(\frac{1}{m}-1\right)} e^{\left\lfloor -Z^{\frac{1}{m}} - (m-1)Y_1 + e^{-Y_1} \right\rfloor} \; , \tag{2.58}$$

where

$$Z = \left(e^{-mX^*} + e^{-mY}\right) \; .$$

TABLE 2-60. Conditional Percentiles Of Wind Speed Shear (M/S) Given Wind Speed (M/S) Applicable Over The 3- To 16-Km Altitude Range, KSC, February.*

h = 100 meters Wind Speed Range (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 3.83 | 3.91 | 3.99 | 4.07 | 4.16 | 4.26 | 4.36 | 4.47 | 4.58 | 4.71 | 4.84 | 4.99 | 5.16 | 5.35 |
| 0.50 | 4.04 | 4.12 | 4.21 | 4.30 | 4.41 | 4.52 | 4.63 | 4.77 | 4.91 | 5.07 | 5.24 | 5.44 | 5.65 | 5.88 |
| 0.60 | 4.22 | 4.30 | 4.39 | 4.49 | 4.60 | 4.72 | 4.86 | 5.00 | 5.17 | 5.35 | 5.56 | 5.78 | 6.02 | 6.27 |
| 0.70 | 4.42 | 4.51 | 4.60 | 4.71 | 4.82 | 4.96 | 5.10 | 5.27 | 5.46 | 5.66 | 5.89 | 6.13 | 6.39 | 6.67 |
| 0.80 | 4.68 | 4.77 | 4.87 | 4.98 | 5.11 | 5.25 | 5.41 | 5.60 | 5.80 | 6.03 | 6.27 | 6.53 | 6.81 | 7.09 |
| 0.85 | 4.86 | 4.95 | 5.05 | 5.16 | 5.29 | 5.44 | 5.61 | 5.80 | 6.02 | 6.25 | 6.51 | 6.77 | 7.05 | 7.34 |
| 0.90 | 5.10 | 5.19 | 5.29 | 5.41 | 5.54 | 5.70 | 5.87 | 6.07 | 6.30 | 6.54 | 6.80 | 7.08 | 7.36 | 7.65 |
| 0.95 | 5.50 | 5.59 | 5.69 | 5.81 | 5.95 | 6.11 | 6.29 | 6.50 | 6.73 | 6.98 | 7.25 | 7.53 | 7.82 | 8.11 |
| 0.98 | 6.01 | 6.11 | 6.21 | 6.33 | 6.47 | 6.63 | 6.82 | 7.03 | 7.27 | 7.53 | 7.80 | 8.08 | 8.37 | 8.66 |
| 0.99 | 6.40 | 6.49 | 6.60 | 6.72 | 6.86 | 7.02 | 7.21 | 7.43 | 7.66 | 7.92 | 8.19 | 8.47 | 8.77 | 9.06 |
| 0.995 | 6.78 | 6.87 | 6.98 | 7.10 | 7.24 | 7.41 | 7.60 | 7.81 | 8.05 | 8.31 | 8.58 | 8.86 | 9.15 | 9.45 |

h = 200 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 5.11 | 5.26 | 5.42 | 5.59 | 5.77 | 5.95 | 6.15 | 6.37 | 6.60 | 6.85 | 7.13 | 7.43 | 7.76 | 8.13 |
| 0.50 | 5.50 | 5.66 | 5.83 | 6.01 | 6.21 | 6.43 | 6.66 | 6.92 | 7.20 | 7.52 | 7.86 | 8.24 | 8.66 | 9.11 |
| 0.60 | 5.81 | 5.98 | 6.16 | 6.35 | 6.57 | 6.81 | 7.07 | 7.36 | 7.68 | 8.04 | 8.43 | 8.86 | 9.32 | 9.81 |
| 0.70 | 6.18 | 6.35 | 6.54 | 6.75 | 6.98 | 7.23 | 7.52 | 7.85 | 8.20 | 8.60 | 9.03 | 9.50 | 9.99 | 10.51 |
| 0.80 | 6.67 | 6.84 | 7.03 | 7.25 | 7.49 | 7.77 | 8.08 | 8.44 | 8.83 | 9.26 | 9.73 | 10.22 | 10.74 | 11.28 |
| 0.85 | 6.99 | 7.17 | 7.36 | 7.58 | 7.83 | 8.12 | 8.45 | 8.82 | 9.22 | 9.67 | 10.15 | 10.66 | 11.18 | 11.72 |
| 0.90 | 7.43 | 7.61 | 7.81 | 8.03 | 8.29 | 8.59 | 8.93 | 9.31 | 9.73 | 10.19 | 10.68 | 11.20 | 11.73 | 12.28 |
| 0.95 | 8.16 | 8.34 | 8.54 | 8.77 | 9.04 | 9.34 | 9.70 | 10.09 | 10.53 | 11.00 | 11.50 | 12.03 | 12.57 | 13.12 |
| 0.98 | 9.10 | 9.28 | 9.49 | 9.72 | 9.99 | 10.30 | 10.66 | 11.06 | 11.51 | 11.99 | 12.50 | 13.03 | 13.57 | 14.12 |
| 0.99 | 9.81 | 9.99 | 10.19 | 10.43 | 10.70 | 11.01 | 11.37 | 11.78 | 12.23 | 12.71 | 13.22 | 13.75 | 14.29 | 14.85 |
| 0.995 | 10.51 | 10.69 | 10.89 | 11.13 | 11.40 | 11.72 | 12.08 | 12.49 | 12.93 | 13.42 | 13.93 | 14.46 | 15.00 | 15.56 |

h = 300 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 5.98 | 6.21 | 6.45 | 6.69 | 6.96 | 7.24 | 7.53 | 7.85 | 8.20 | 8.57 | 8.99 | 9.44 | 9.94 | 10.49 |
| 0.50 | 6.52 | 6.75 | 7.01 | 7.28 | 7.57 | 7.89 | 8.24 | 8.62 | 9.04 | 9.50 | 10.01 | 10.56 | 11.17 | 11.82 |
| 0.60 | 6.96 | 7.20 | 7.46 | 7.75 | 8.07 | 8.41 | 8.80 | 9.22 | 9.69 | 10.21 | 10.78 | 11.40 | 12.07 | 12.77 |
| 0.70 | 7.47 | 7.72 | 7.99 | 8.29 | 8.63 | 9.00 | 9.42 | 9.89 | 10.41 | 10.98 | 11.60 | 12.27 | 12.98 | 13.71 |
| 0.80 | 8.13 | 8.39 | 8.67 | 8.99 | 9.34 | 9.74 | 10.20 | 10.71 | 11.27 | 11.89 | 12.55 | 13.25 | 13.99 | 14.74 |
| 0.85 | 8.58 | 8.84 | 9.12 | 9.45 | 9.81 | 10.23 | 10.70 | 11.22 | 11.81 | 12.44 | 13.13 | 13.84 | 14.59 | 15.35 |
| 0.90 | 9.19 | 9.45 | 9.74 | 10.07 | 10.44 | 10.87 | 11.36 | 11.90 | 12.51 | 13.16 | 13.86 | 14.59 | 15.34 | 16.11 |
| 0.95 | 10.19 | 10.46 | 10.75 | 11.09 | 11.47 | 11.91 | 12.41 | 12.98 | 13.60 | 14.27 | 14.98 | 15.72 | 16.48 | 17.26 |
| 0.98 | 11.49 | 11.76 | 12.05 | 12.39 | 12.78 | 13.23 | 13.74 | 14.32 | 14.95 | 15.63 | 16.35 | 17.09 | 17.86 | 18.64 |
| 0.99 | 12.46 | 12.73 | 13.03 | 13.37 | 13.76 | 14.21 | 14.73 | 15.30 | 15.94 | 16.62 | 17.34 | 18.09 | 18.86 | 19.64 |
| 0.995 | 13.43 | 13.70 | 14.00 | 14.34 | 14.73 | 15.18 | 15.70 | 16.28 | 16.91 | 17.60 | 18.32 | 19.07 | 19.84 | 20.62 |

h = 400 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 6.65 | 6.94 | 7.25 | 7.58 | 7.93 | 8.30 | 8.69 | 9.11 | 9.57 | 10.06 | 10.61 | 11.21 | 11.87 | 12.59 |
| 0.50 | 7.30 | 7.61 | 7.95 | 8.30 | 8.68 | 9.10 | 9.56 | 10.05 | 10.60 | 11.21 | 11.87 | 12.59 | 13.37 | 14.21 |
| 0.60 | 7.84 | 8.16 | 8.51 | 8.88 | 9.29 | 9.75 | 10.24 | 10.80 | 11.41 | 12.08 | 12.81 | 13.61 | 14.46 | 15.35 |
| 0.70 | 8.48 | 8.80 | 9.16 | 9.55 | 9.99 | 10.47 | 11.01 | 11.62 | 12.29 | 13.02 | 13.81 | 14.66 | 15.56 | 16.48 |
| 0.80 | 9.29 | 9.63 | 9.99 | 10.40 | 10.86 | 11.38 | 11.96 | 12.62 | 13.33 | 14.12 | 14.96 | 15.85 | 16.78 | 17.73 |
| 0.85 | 9.84 | 10.18 | 10.55 | 10.97 | 11.44 | 11.97 | 12.58 | 13.25 | 14.00 | 14.80 | 15.66 | 16.57 | 17.51 | 18.47 |
| 0.90 | 10.59 | 10.93 | 11.31 | 11.73 | 12.22 | 12.77 | 13.39 | 14.08 | 14.85 | 15.68 | 16.56 | 17.48 | 18.43 | 19.40 |
| 0.95 | 11.83 | 12.17 | 12.56 | 12.99 | 13.48 | 14.05 | 14.69 | 15.40 | 16.19 | 17.04 | 17.93 | 18.87 | 19.82 | 20.80 |
| 0.98 | 13.43 | 13.77 | 14.16 | 14.60 | 15.10 | 15.67 | 16.32 | 17.05 | 17.85 | 18.71 | 19.61 | 20.55 | 21.51 | 22.49 |
| 0.99 | 14.62 | 14.97 | 15.36 | 15.80 | 16.30 | 16.88 | 17.53 | 18.26 | 19.07 | 19.93 | 20.83 | 21.77 | 22.74 | 23.72 |
| 0.995 | 15.82 | 16.16 | 16.55 | 16.99 | 17.49 | 18.07 | 18.73 | 19.46 | 20.27 | 21.13 | 22.04 | 22.98 | 23.95 | 24.93 |

* h = height interval (m)

TABLE 2-60. Conditional Percentiles Of Wind Speed Shear (M/S) Given Wind Speed (M/S) Applicable Over The 3- To 16-Km Altitude Range, KSC, February (Continued).*

h = 500 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 7.18 | 7.54 | 7.92 | 8.33 | 8.75 | 9.20 | 9.69 | 10.21 | 10.77 | 11.39 | 12.07 | 12.81 | 13.62 | 14.50 |
| 0.50 | 7.94 | 8.32 | 8.72 | 9.16 | 9.63 | 10.14 | 10.70 | 11.30 | 11.97 | 12.71 | 13.51 | 14.39 | 15.34 | 16.34 |
| 0.60 | 8.56 | 8.95 | 9.37 | 9.83 | 10.33 | 10.88 | 11.49 | 12.16 | 12.90 | 13.72 | 14.60 | 15.56 | 16.58 | 17.64 |
| 0.70 | 9.29 | 9.69 | 10.13 | 10.61 | 11.14 | 11.72 | 12.38 | 13.11 | 13.92 | 14.80 | 15.75 | 16.76 | 17.82 | 18.93 |
| 0.80 | 10.24 | 10.65 | 11.10 | 11.59 | 12.15 | 12.78 | 13.48 | 14.26 | 15.12 | 16.06 | 17.06 | 18.12 | 19.22 | 20.35 |
| 0.85 | 10.88 | 11.29 | 11.74 | 12.25 | 12.82 | 13.46 | 14.19 | 14.99 | 15.88 | 16.84 | 17.87 | 18.94 | 20.06 | 21.20 |
| 0.90 | 11.74 | 12.16 | 12.62 | 13.13 | 13.72 | 14.38 | 15.12 | 15.96 | 16.87 | 17.85 | 18.90 | 19.99 | 21.11 | 22.26 |
| 0.95 | 13.18 | 13.60 | 14.06 | 14.59 | 15.18 | 15.86 | 16.63 | 17.48 | 18.42 | 19.42 | 20.49 | 21.59 | 22.72 | 23.88 |
| 0.98 | 15.03 | 15.45 | 15.92 | 16.45 | 17.05 | 17.74 | 18.52 | 19.39 | 20.34 | 21.35 | 22.43 | 23.54 | 24.67 | 25.83 |
| 0.99 | 16.42 | 16.84 | 17.31 | 17.84 | 18.45 | 19.14 | 19.92 | 20.79 | 21.75 | 22.77 | 23.84 | 24.95 | 26.09 | 27.25 |
| 0.995 | 17.80 | 18.22 | 18.69 | 19.22 | 19.83 | 20.52 | 21.31 | 22.18 | 23.14 | 24.16 | 25.24 | 26.35 | 27.49 | 28.65 |

h = 600 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 7.60 | 8.03 | 8.49 | 8.96 | 9.47 | 10.00 | 10.57 | 11.19 | 11.86 | 12.59 | 13.39 | 14.26 | 15.22 | 16.25 |
| 0.50 | 8.45 | 8.90 | 9.38 | 9.89 | 10.44 | 11.04 | 11.70 | 12.41 | 13.20 | 14.06 | 15.00 | 16.02 | 17.12 | 18.28 |
| 0.60 | 9.15 | 9.61 | 10.11 | 10.64 | 11.23 | 11.87 | 12.58 | 13.37 | 14.23 | 15.17 | 16.20 | 17.30 | 18.47 | 19.69 |
| 0.70 | 9.97 | 10.44 | 10.95 | 11.51 | 12.13 | 12.81 | 13.57 | 14.42 | 15.35 | 16.37 | 17.46 | 18.62 | 19.84 | 21.10 |
| 0.80 | 11.02 | 11.50 | 12.03 | 12.61 | 13.26 | 13.98 | 14.79 | 15.70 | 16.69 | 17.77 | 18.91 | 20.12 | 21.38 | 22.66 |
| 0.85 | 11.73 | 12.22 | 12.75 | 13.34 | 14.00 | 14.75 | 15.58 | 16.51 | 17.53 | 18.63 | 19.81 | 21.03 | 22.30 | 23.60 |
| 0.90 | 12.70 | 13.19 | 13.73 | 14.33 | 15.00 | 15.77 | 16.63 | 17.58 | 18.63 | 19.76 | 20.95 | 22.19 | 23.47 | 24.78 |
| 0.95 | 14.30 | 14.80 | 15.34 | 15.95 | 16.64 | 17.42 | 18.30 | 19.28 | 20.35 | 21.50 | 22.71 | 23.97 | 25.26 | 26.57 |
| 0.98 | 16.37 | 16.87 | 17.41 | 18.03 | 18.73 | 19.52 | 20.41 | 21.41 | 22.49 | 23.65 | 24.87 | 26.14 | 27.43 | 28.75 |
| 0.99 | 17.92 | 18.41 | 18.96 | 19.58 | 20.28 | 21.08 | 21.98 | 22.97 | 24.06 | 25.23 | 26.45 | 27.72 | 29.02 | 30.33 |
| 0.995 | 19.46 | 19.96 | 20.51 | 21.12 | 21.83 | 22.62 | 23.52 | 24.52 | 25.62 | 26.78 | 28.01 | 29.28 | 30.57 | 31.89 |

h = 700 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 7.92 | 8.41 | 8.93 | 9.47 | 10.04 | 10.66 | 11.31 | 12.01 | 12.77 | 13.60 | 14.52 | 15.51 | 16.60 | 17.76 |
| 0.50 | 8.84 | 9.35 | 9.90 | 10.48 | 11.11 | 11.79 | 12.52 | 13.33 | 14.22 | 15.19 | 16.25 | 17.39 | 18.62 | 19.92 |
| 0.60 | 9.60 | 10.12 | 10.69 | 11.29 | 11.96 | 12.68 | 13.48 | 14.36 | 15.33 | 16.39 | 17.53 | 18.77 | 20.07 | 21.43 |
| 0.70 | 10.49 | 11.02 | 11.60 | 12.23 | 12.93 | 13.70 | 14.55 | 15.49 | 16.54 | 17.67 | 18.89 | 20.18 | 21.54 | 22.94 |
| 0.80 | 11.64 | 12.18 | 12.77 | 13.43 | 14.15 | 14.96 | 15.87 | 16.87 | 17.98 | 19.17 | 20.45 | 21.79 | 23.18 | 24.61 |
| 0.85 | 12.41 | 12.96 | 13.56 | 14.22 | 14.96 | 15.79 | 16.72 | 17.75 | 18.89 | 20.11 | 21.41 | 22.77 | 24.18 | 25.62 |
| 0.90 | 13.46 | 14.02 | 14.62 | 15.29 | 16.05 | 16.90 | 17.85 | 18.91 | 20.08 | 21.32 | 22.64 | 24.02 | 25.44 | 26.89 |
| 0.95 | 15.21 | 15.76 | 16.38 | 17.06 | 17.83 | 18.70 | 19.67 | 20.76 | 21.94 | 23.22 | 24.56 | 25.95 | 27.38 | 28.83 |
| 0.98 | 17.46 | 18.02 | 18.63 | 19.32 | 20.10 | 20.98 | 21.97 | 23.07 | 24.27 | 25.55 | 26.90 | 28.30 | 29.74 | 31.20 |
| 0.99 | 19.14 | 19.70 | 20.32 | 21.01 | 21.79 | 22.67 | 23.67 | 24.77 | 25.98 | 27.27 | 28.62 | 30.02 | 31.46 | 32.92 |
| 0.995 | 20.82 | 21.38 | 22.00 | 22.69 | 23.47 | 24.36 | 25.35 | 26.46 | 27.67 | 28.96 | 30.31 | 31.72 | 33.16 | 34.62 |

h = 800 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 8.27 | 8.83 | 9.41 | 10.02 | 10.67 | 11.37 | 12.10 | 12.90 | 13.77 | 14.71 | 15.74 | 16.86 | 18.08 | 19.40 |
| 0.50 | 9.26 | 9.84 | 10.45 | 11.11 | 11.82 | 12.58 | 13.41 | 14.32 | 15.32 | 16.41 | 17.60 | 18.88 | 20.24 | 21.68 |
| 0.60 | 10.07 | 10.66 | 11.30 | 11.98 | 12.73 | 13.54 | 14.44 | 15.43 | 16.51 | 17.70 | 18.97 | 20.33 | 21.77 | 23.27 |
| 0.70 | 11.02 | 11.63 | 12.28 | 12.99 | 13.77 | 14.63 | 15.59 | 16.64 | 17.81 | 19.06 | 20.41 | 21.84 | 23.33 | 24.86 |
| 0.80 | 12.25 | 12.87 | 13.53 | 14.27 | 15.08 | 15.99 | 17.00 | 18.12 | 19.35 | 20.67 | 22.07 | 23.54 | 25.07 | 26.63 |
| 0.85 | 13.08 | 13.70 | 14.37 | 15.12 | 15.95 | 16.88 | 17.92 | 19.06 | 20.32 | 21.67 | 23.10 | 24.59 | 26.13 | 27.70 |
| 0.90 | 14.21 | 14.83 | 15.51 | 16.27 | 17.11 | 18.06 | 19.13 | 20.30 | 21.59 | 22.96 | 24.41 | 25.92 | 27.47 | 29.05 |
| 0.95 | 16.07 | 16.70 | 17.39 | 18.15 | 19.02 | 19.99 | 21.07 | 22.28 | 23.58 | 24.98 | 26.45 | 27.97 | 29.53 | 31.12 |
| 0.98 | 18.48 | 19.11 | 19.80 | 20.57 | 21.44 | 22.43 | 23.53 | 24.75 | 26.07 | 27.48 | 28.96 | 30.49 | 32.06 | 33.65 |
| 0.99 | 20.28 | 20.91 | 21.60 | 22.38 | 23.25 | 24.24 | 25.35 | 26.57 | 27.90 | 29.31 | 30.79 | 32.33 | 33.90 | 35.49 |
| 0.995 | 22.07 | 22.70 | 23.40 | 24.18 | 25.05 | 26.04 | 27.15 | 28.37 | 29.70 | 31.12 | 32.60 | 34.14 | 35.71 | 37.30 |

* h = height interval (m)

TABLE 2-60. Conditional Percentiles Of Wind Speed Shear (M/S) Given Wind Speed (M/S) Applicable Over The 3- To 16-Km Altitude Range, KSC, February (Continued).*

h = 900 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 8.59 | 9.21 | 9.85 | 10.54 | 11.26 | 12.03 | 12.85 | 13.74 | 14.71 | 15.76 | 16.90 | 18.16 | 19.50 | 20.95 |
| 0.50 | 9.63 | 10.27 | 10.96 | 11.69 | 12.47 | 13.32 | 14.25 | 15.25 | 16.36 | 17.56 | 18.87 | 20.27 | 21.76 | 23.33 |
| 0.60 | 10.49 | 11.15 | 11.85 | 12.61 | 13.44 | 14.34 | 15.33 | 16.43 | 17.62 | 18.92 | 20.31 | 21.80 | 23.36 | 24.98 |
| 0.70 | 11.50 | 12.16 | 12.89 | 13.67 | 14.54 | 15.49 | 16.55 | 17.71 | 18.98 | 20.36 | 21.82 | 23.37 | 24.98 | 26.64 |
| 0.80 | 12.80 | 13.48 | 14.21 | 15.03 | 15.93 | 16.93 | 18.04 | 19.27 | 20.61 | 22.05 | 23.57 | 25.16 | 26.81 | 28.49 |
| 0.85 | 13.67 | 14.35 | 15.10 | 15.93 | 16.84 | 17.87 | 19.01 | 20.26 | 21.63 | 23.10 | 24.65 | 26.26 | 27.92 | 29.62 |
| 0.90 | 14.86 | 15.55 | 16.30 | 17.14 | 18.08 | 19.12 | 20.29 | 21.57 | 22.97 | 24.46 | 26.03 | 27.66 | 29.33 | 31.03 |
| 0.95 | 16.83 | 17.52 | 18.28 | 19.13 | 20.08 | 21.15 | 22.34 | 23.65 | 25.07 | 26.59 | 28.18 | 29.82 | 31.50 | 33.21 |
| 0.98 | 19.37 | 20.06 | 20.83 | 21.69 | 22.65 | 23.73 | 24.93 | 26.26 | 27.70 | 29.22 | 30.82 | 32.47 | 34.16 | 35.87 |
| 0.99 | 21.27 | 21.97 | 22.74 | 23.59 | 24.56 | 25.64 | 26.85 | 28.18 | 29.62 | 31.15 | 32.76 | 34.41 | 36.10 | 37.81 |
| 0.995 | 23.16 | 23.86 | 24.63 | 25.49 | 26.45 | 27.54 | 28.75 | 30.08 | 31.53 | 33.06 | 34.67 | 36.32 | 38.01 | 39.72 |

h = 1,000 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 8.88 | 9.55 | 10.27 | 11.02 | 11.81 | 12.65 | 13.56 | 14.54 | 15.60 | 16.75 | 18.01 | 19.38 | 20.86 | 22.42 |
| 0.50 | 9.97 | 10.67 | 11.42 | 12.22 | 13.08 | 14.01 | 15.02 | 16.13 | 17.34 | 18.65 | 20.07 | 21.59 | 23.20 | 24.88 |
| 0.60 | 10.87 | 11.59 | 12.36 | 13.19 | 14.10 | 15.08 | 16.17 | 17.36 | 18.65 | 20.07 | 21.57 | 23.17 | 24.85 | 26.58 |
| 0.70 | 11.92 | 12.65 | 13.44 | 14.30 | 15.25 | 16.29 | 17.44 | 18.70 | 20.08 | 21.56 | 23.14 | 24.80 | 26.53 | 28.30 |
| 0.80 | 13.28 | 14.02 | 14.83 | 15.72 | 16.70 | 17.79 | 19.00 | 20.33 | 21.78 | 23.32 | 24.96 | 26.66 | 28.42 | 30.22 |
| 0.85 | 14.19 | 14.94 | 15.76 | 16.66 | 17.66 | 18.77 | 20.01 | 21.37 | 22.84 | 24.42 | 26.08 | 27.80 | 29.58 | 31.38 |
| 0.90 | 15.43 | 16.19 | 17.02 | 17.93 | 18.95 | 20.08 | 21.35 | 22.73 | 24.24 | 25.84 | 27.52 | 29.25 | 31.04 | 32.85 |
| 0.95 | 17.49 | 18.25 | 19.09 | 20.01 | 21.05 | 22.20 | 23.49 | 24.91 | 26.44 | 28.06 | 29.76 | 31.51 | 33.30 | 35.12 |
| 0.98 | 20.14 | 20.91 | 21.75 | 22.68 | 23.73 | 24.90 | 26.20 | 27.63 | 29.17 | 30.81 | 32.52 | 34.28 | 36.07 | 37.90 |
| 0.99 | 22.13 | 22.89 | 23.74 | 24.67 | 25.72 | 26.90 | 28.20 | 29.64 | 31.19 | 32.83 | 34.54 | 36.30 | 38.10 | 39.92 |
| 0.995 | 24.11 | 24.87 | 25.72 | 26.65 | 27.70 | 28.88 | 30.19 | 31.63 | 33.18 | 34.82 | 36.53 | 38.30 | 40.10 | 41.92 |

h = 1,500 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 10.03 | 10.98 | 11.98 | 13.04 | 14.16 | 15.35 | 16.64 | 18.02 | 19.51 | 21.14 | 22.88 | 24.74 | 26.72 | 28.79 |
| 0.50 | 11.29 | 12.27 | 13.32 | 14.44 | 15.64 | 16.94 | 18.34 | 19.87 | 21.52 | 23.30 | 25.19 | 27.19 | 29.28 | 31.43 |
| 0.60 | 12.31 | 13.32 | 14.40 | 15.55 | 16.81 | 18.17 | 19.66 | 21.28 | 23.02 | 24.88 | 26.86 | 28.93 | 31.07 | 33.26 |
| 0.70 | 13.51 | 14.54 | 15.64 | 16.83 | 18.13 | 19.56 | 21.12 | 22.80 | 24.63 | 26.57 | 28.61 | 30.73 | 32.90 | 35.12 |
| 0.80 | 15.06 | 16.10 | 17.22 | 18.45 | 19.80 | 21.28 | 22.90 | 24.65 | 26.55 | 28.54 | 30.62 | 32.78 | 34.98 | 37.22 |
| 0.85 | 16.10 | 17.14 | 18.28 | 19.52 | 20.89 | 22.40 | 24.04 | 25.83 | 27.75 | 29.77 | 31.88 | 34.05 | 36.26 | 38.50 |
| 0.90 | 17.51 | 18.57 | 19.71 | 20.97 | 22.36 | 23.89 | 25.57 | 27.38 | 29.32 | 31.36 | 33.49 | 35.67 | 37.89 | 40.14 |
| 0.95 | 19.85 | 20.91 | 22.07 | 23.34 | 24.75 | 26.30 | 28.00 | 29.85 | 31.81 | 33.87 | 36.01 | 38.21 | 40.44 | 42.69 |
| 0.98 | 22.86 | 23.93 | 25.09 | 26.37 | 27.79 | 29.36 | 31.08 | 32.94 | 34.91 | 36.99 | 39.13 | 41.33 | 43.57 | 45.83 |
| 0.99 | 25.12 | 26.19 | 27.35 | 28.63 | 30.06 | 31.63 | 33.35 | 35.22 | 37.20 | 39.28 | 41.43 | 43.63 | 45.86 | 48.13 |
| 0.995 | 27.37 | 28.43 | 29.60 | 30.88 | 32.31 | 33.88 | 35.61 | 37.47 | 39.46 | 41.54 | 43.69 | 45.89 | 48.13 | 50.39 |

h = 2,000 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 10.91 | 12.10 | 13.35 | 14.67 | 16.07 | 17.56 | 19.16 | 20.88 | 22.73 | 24.72 | 26.84 | 29.09 | 31.44 | 33.86 |
| 0.50 | 12.24 | 13.47 | 14.77 | 16.16 | 17.64 | 19.25 | 20.98 | 22.85 | 24.84 | 26.98 | 29.23 | 31.58 | 34.01 | 36.49 |
| 0.60 | 13.32 | 14.58 | 15.91 | 17.34 | 18.89 | 20.57 | 22.37 | 24.33 | 26.42 | 28.63 | 30.94 | 33.35 | 35.81 | 38.33 |
| 0.70 | 14.59 | 15.86 | 17.22 | 18.69 | 20.29 | 22.03 | 23.91 | 25.93 | 28.09 | 30.37 | 32.74 | 35.18 | 37.68 | 40.21 |
| 0.80 | 16.21 | 17.50 | 18.89 | 20.40 | 22.05 | 23.84 | 25.78 | 27.87 | 30.09 | 32.41 | 34.82 | 37.29 | 39.81 | 42.36 |
| 0.85 | 17.30 | 18.60 | 20.01 | 21.53 | 23.20 | 25.02 | 26.99 | 29.10 | 31.35 | 33.69 | 36.12 | 38.60 | 41.13 | 43.68 |
| 0.90 | 18.79 | 20.10 | 21.51 | 23.05 | 24.74 | 26.59 | 28.58 | 30.72 | 32.99 | 35.35 | 37.79 | 40.29 | 42.82 | 45.38 |
| 0.95 | 21.24 | 22.56 | 23.98 | 25.54 | 27.25 | 29.12 | 31.14 | 33.30 | 35.59 | 37.97 | 40.43 | 42.93 | 45.47 | 48.04 |
| 0.98 | 24.41 | 25.73 | 27.16 | 28.73 | 30.45 | 32.33 | 34.36 | 36.54 | 38.84 | 41.23 | 43.70 | 46.21 | 48.75 | 51.32 |
| 0.99 | 26.77 | 28.10 | 29.53 | 31.10 | 32.82 | 34.71 | 36.75 | 38.94 | 41.24 | 43.63 | 46.10 | 48.61 | 51.15 | 53.72 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.995 | 29.13 | 30.45 | 31.89 | 33.46 | 35.19 | 37.07 | 39.12 | 41.30 | 43.61 | 46.01 | 48.47 | 50.98 | 53.53 | 56.10 |

* h = height interval (m)

TABLE 2-60. Conditional Percentiles Of Wind Speed Shear (m/s )Given Wind Speed (m/s) Applicable Over The 3- To 16-Km Altitude Range, KSC, February (Continued).*

h = 2,500 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 11.64 | 13.04 | 14.51 | 16.06 | 17.69 | 19.43 | 21.31 | 23.30 | 25.45 | 27.73 | 30.14 | 32.66 | 35.27 | 37.95 |
| 0.50 | 13.00 | 14.43 | 15.96 | 17.58 | 19.30 | 21.17 | 23.16 | 25.31 | 27.58 | 29.98 | 32.50 | 35.11 | 37.79 | 40.52 |
| 0.60 | 14.10 | 15.56 | 17.12 | 18.79 | 20.58 | 22.51 | 24.58 | 26.80 | 29.16 | 31.64 | 34.21 | 36.87 | 39.58 | 42.34 |
| 0.70 | 15.38 | 16.87 | 18.45 | 20.16 | 22.00 | 24.00 | 26.13 | 28.42 | 30.84 | 33.38 | 36.00 | 38.68 | 41.41 | 44.18 |
| 0.80 | 17.04 | 18.54 | 20.16 | 21.90 | 23.79 | 25.83 | 28.04 | 30.38 | 32.85 | 35.42 | 38.07 | 40.78 | 43.54 | 46.32 |
| 0.85 | 18.14 | 19.66 | 21.28 | 23.05 | 24.96 | 27.03 | 29.26 | 31.62 | 34.12 | 36.71 | 39.37 | 42.09 | 44.85 | 47.64 |
| 0.90 | 19.65 | 21.17 | 22.81 | 24.59 | 26.52 | 28.62 | 30.87 | 33.26 | 35.78 | 38.38 | 41.06 | 43.79 | 46.56 | 49.34 |
| 0.95 | 22.13 | 23.66 | 25.32 | 27.11 | 29.06 | 31.18 | 33.46 | 35.87 | 38.40 | 41.03 | 43.72 | 46.45 | 49.22 | 52.02 |
| 0.98 | 25.34 | 26.87 | 28.53 | 30.34 | 32.30 | 34.43 | 36.72 | 39.15 | 41.69 | 44.32 | 47.02 | 49.76 | 52.53 | 55.33 |
| 0.99 | 27.73 | 29.27 | 30.93 | 32.74 | 34.71 | 36.84 | 39.14 | 41.57 | 44.11 | 46.75 | 49.45 | 52.19 | 54.96 | 57.76 |
| 0.995 | 30.12 | 31.66 | 33.32 | 35.13 | 37.10 | 39.24 | 41.53 | 43.96 | 46.51 | 49.15 | 51.85 | 54.59 | 57.37 | 60.16 |

h = 3,000 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 12.29 | 13.86 | 15.51 | 17.25 | 19.10 | 21.05 | 23.16 | 25.38 | 27.76 | 30.28 | 32.93 | 35.67 | 38.49 | 41.37 |
| 0.50 | 13.64 | 15.26 | 16.96 | 18.78 | 20.72 | 22.79 | 25.01 | 27.38 | 29.87 | 32.50 | 35.23 | 38.04 | 40.91 | 43.83 |
| 0.60 | 14.75 | 16.39 | 18.13 | 20.00 | 22.00 | 24.13 | 26.42 | 28.87 | 31.44 | 34.12 | 36.90 | 39.75 | 42.65 | 45.58 |
| 0.70 | 16.02 | 17.69 | 19.46 | 21.37 | 23.42 | 25.62 | 27.97 | 30.47 | 33.10 | 35.83 | 38.65 | 41.52 | 44.43 | 47.38 |
| 0.80 | 17.67 | 19.35 | 21.16 | 23.11 | 25.20 | 27.45 | 29.86 | 32.40 | 35.07 | 37.84 | 40.68 | 43.58 | 46.51 | 49.47 |
| 0.85 | 18.77 | 20.47 | 22.28 | 24.25 | 26.36 | 28.64 | 31.07 | 33.64 | 36.33 | 39.11 | 41.97 | 44.87 | 47.81 | 50.77 |
| 0.90 | 20.26 | 21.97 | 23.80 | 25.78 | 27.92 | 30.22 | 32.67 | 35.26 | 37.97 | 40.77 | 43.63 | 46.54 | 49.49 | 52.45 |
| 0.95 | 22.73 | 24.45 | 26.29 | 28.29 | 30.44 | 32.77 | 35.24 | 37.86 | 40.58 | 43.39 | 46.26 | 49.18 | 52.13 | 55.10 |
| 0.98 | 25.91 | 27.64 | 29.49 | 31.49 | 33.66 | 35.99 | 38.48 | 41.11 | 43.84 | 46.66 | 49.54 | 52.46 | 55.41 | 58.38 |
| 0.99 | 28.29 | 30.02 | 31.87 | 33.88 | 36.05 | 38.39 | 40.88 | 43.51 | 46.25 | 49.07 | 51.95 | 54.87 | 57.82 | 60.79 |
| 0.995 | 30.66 | 32.39 | 34.24 | 36.25 | 38.43 | 40.77 | 43.26 | 45.89 | 48.63 | 51.45 | 54.33 | 57.26 | 60.21 | 63.18 |

h = 3,500 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 12.87 | 14.61 | 16.41 | 18.32 | 20.35 | 22.49 | 24.78 | 27.19 | 29.76 | 32.47 | 35.30 | 38.21 | 41.19 | 44.22 |
| 0.50 | 14.21 | 15.98 | 17.85 | 19.84 | 21.96 | 24.20 | 26.61 | 29.16 | 31.83 | 34.63 | 37.53 | 40.50 | 43.53 | 46.60 |
| 0.60 | 15.30 | 17.10 | 19.01 | 21.04 | 23.21 | 25.53 | 28.00 | 30.62 | 33.36 | 36.21 | 39.15 | 42.15 | 45.20 | 48.28 |
| 0.70 | 16.56 | 18.38 | 20.32 | 22.40 | 24.62 | 26.99 | 29.52 | 32.20 | 34.99 | 37.88 | 40.85 | 43.87 | 46.93 | 50.02 |
| 0.80 | 18.18 | 20.02 | 22.00 | 24.10 | 26.38 | 28.80 | 31.37 | 34.09 | 36.92 | 39.85 | 42.84 | 45.87 | 48.95 | 52.05 |
| 0.85 | 19.26 | 21.12 | 23.10 | 25.23 | 27.52 | 29.96 | 32.57 | 35.31 | 38.16 | 41.09 | 44.09 | 47.14 | 50.22 | 53.32 |
| 0.90 | 20.73 | 22.60 | 24.60 | 26.74 | 29.05 | 31.52 | 34.14 | 36.90 | 39.76 | 42.71 | 45.72 | 48.77 | 51.86 | 54.96 |
| 0.95 | 23.16 | 25.04 | 27.05 | 29.21 | 31.53 | 34.03 | 36.67 | 39.44 | 42.32 | 45.29 | 48.30 | 51.36 | 54.45 | 57.56 |
| 0.98 | 26.29 | 28.17 | 30.19 | 32.36 | 34.70 | 37.20 | 39.85 | 42.64 | 45.53 | 48.49 | 51.52 | 54.58 | 57.67 | 60.78 |
| 0.99 | 28.63 | 30.51 | 32.53 | 34.71 | 37.05 | 39.55 | 42.21 | 45.00 | 47.89 | 50.86 | 53.89 | 56.95 | 60.04 | 63.15 |
| 0.995 | 30.96 | 32.84 | 34.86 | 37.04 | 39.38 | 41.89 | 44.55 | 47.34 | 50.23 | 53.20 | 56.23 | 59.29 | 62.38 | 65.49 |

h = 4,000 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 13.41 | 15.27 | 17.23 | 19.29 | 21.46 | 23.76 | 26.21 | 28.79 | 31.52 | 34.38 | 37.35 | 40.40 | 43.51 | 46.66 |
| 0.50 | 14.72 | 16.63 | 18.65 | 20.78 | 23.04 | 25.45 | 28.01 | 30.71 | 33.53 | 36.47 | 39.50 | 42.61 | 45.76 | 48.95 |
| 0.60 | 15.79 | 17.73 | 19.78 | 21.96 | 24.28 | 26.75 | 29.38 | 32.13 | 35.01 | 38.00 | 41.06 | 44.19 | 47.36 | 50.57 |
| 0.70 | 17.03 | 18.99 | 21.07 | 23.29 | 25.66 | 28.18 | 30.86 | 33.67 | 36.60 | 39.62 | 42.71 | 45.86 | 49.05 | 52.24 |
| 0.80 | 18.61 | 20.60 | 22.71 | 24.97 | 27.37 | 29.95 | 32.67 | 35.53 | 38.49 | 41.54 | 44.65 | 47.81 | 50.99 | 54.20 |
| 0.85 | 19.67 | 21.67 | 23.79 | 26.06 | 28.50 | 31.09 | 33.83 | 36.70 | 39.68 | 42.74 | 45.87 | 49.04 | 52.23 | 55.44 |
| 0.90 | 21.11 | 23.12 | 25.25 | 27.54 | 29.99 | 32.61 | 35.37 | 38.26 | 41.25 | 44.33 | 47.46 | 50.63 | 53.83 | 57.04 |
| 0.95 | 23.48 | 25.50 | 27.65 | 29.95 | 32.43 | 35.06 | 37.84 | 40.74 | 43.75 | 46.83 | 49.97 | 53.15 | 56.35 | 59.57 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.98 | 26.54 | 28.56 | 30.72 | 33.03 | 35.51 | 38.16 | 40.95 | 43.86 | 46.08 | 49.97 | 53.11 | 56.29 | 59.49 | 62.71 |
| 0.99 | 28.82 | 30.85 | 33.01 | 35.33 | 37.81 | 40.46 | 43.25 | 46.17 | 49.19 | 52.28 | 55.42 | 58.60 | 61.81 | 65.03 |
| 0.995 | 31.10 | 33.12 | 35.28 | 37.60 | 40.09 | 42.74 | 45.53 | 48.45 | 51.47 | 54.57 | 57.71 | 60.89 | 64.09 | 67.32 |

* h = height interval (m)

TABLE 2-60. Conditional Percentiles Of Wind Speed Shear (M/S) Given Wind Speed (M/S) Applicable Over The 3- To 16-Km Altitude Range, KSC, February (Continued).*

h = 5,000 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 14.39 | 16.49 | 18.66 | 20.97 | 23.38 | 25.96 | 28.65 | 31.49 | 34.46 | 37.56 | 40.74 | 43.99 | 47.30 | 50.65 |
| 0.50 | 15.64 | 17.78 | 20.02 | 22.39 | 24.90 | 27.57 | 30.35 | 33.28 | 36.34 | 39.50 | 42.73 | 46.03 | 49.37 | 52.74 |
| 0.60 | 16.66 | 18.82 | 21.11 | 23.52 | 26.09 | 28.79 | 31.64 | 34.62 | 37.73 | 40.92 | 44.18 | 47.49 | 50.85 | 54.22 |
| 0.70 | 17.83 | 20.02 | 22.33 | 24.79 | 27.40 | 30.15 | 33.05 | 36.08 | 39.21 | 42.43 | 45.72 | 49.04 | 52.40 | 55.79 |
| 0.80 | 19.33 | 21.55 | 23.89 | 26.38 | 29.02 | 31.82 | 34.76 | 37.82 | 40.99 | 44.23 | 47.53 | 50.87 | 54.24 | 57.64 |
| 0.85 | 20.34 | 22.56 | 24.91 | 27.42 | 30.08 | 32.90 | 35.86 | 38.95 | 42.12 | 45.38 | 48.68 | 52.02 | 55.39 | 58.78 |
| 0.90 | 21.70 | 23.93 | 26.30 | 28.82 | 31.50 | 34.34 | 37.32 | 40.41 | 43.61 | 46.87 | 50.18 | 53.53 | 56.90 | 60.29 |
| 0.95 | 23.94 | 26.19 | 28.57 | 31.10 | 33.80 | 36.65 | 39.65 | 42.76 | 45.96 | 49.23 | 52.55 | 55.91 | 59.28 | 62.67 |
| 0.98 | 26.83 | 29.08 | 31.47 | 34.02 | 36.72 | 39.59 | 42.59 | 45.71 | 48.92 | 52.19 | 55.51 | 58.87 | 62.25 | 65.64 |
| 0.99 | 28.99 | 31.25 | 33.64 | 36.18 | 38.89 | 41.76 | 44.77 | 47.89 | 51.10 | 54.38 | 57.70 | 61.06 | 64.43 | 67.83 |
| 0.995 | 31.15 | 33.40 | 35.79 | 38.34 | 41.05 | 43.92 | 46.93 | 50.05 | 53.26 | 56.54 | 59.86 | 63.22 | 66.60 | 69.99 |

h = 6,000 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 15.27 | 17.53 | 19.91 | 22.38 | 25.02 | 27.75 | 30.64 | 33.68 | 36.84 | 40.10 | 43.44 | 46.84 | 50.28 | 53.76 |
| 0.50 | 16.45 | 18.77 | 21.19 | 23.75 | 26.45 | 29.27 | 32.25 | 35.36 | 38.59 | 41.90 | 45.28 | 48.71 | 52.18 | 55.68 |
| 0.60 | 17.41 | 19.76 | 22.22 | 24.82 | 27.55 | 30.44 | 33.47 | 36.63 | 39.89 | 43.23 | 46.63 | 50.08 | 53.55 | 57.05 |
| 0.70 | 18.52 | 20.89 | 23.39 | 26.01 | 28.79 | 31.73 | 34.81 | 37.99 | 41.28 | 44.65 | 48.07 | 51.53 | 55.01 | 58.51 |
| 0.80 | 19.94 | 22.33 | 24.85 | 27.51 | 30.33 | 33.31 | 36.41 | 39.63 | 42.95 | 46.33 | 49.77 | 53.23 | 56.72 | 60.23 |
| 0.85 | 20.88 | 23.29 | 25.82 | 28.50 | 31.34 | 34.32 | 37.44 | 40.67 | 44.00 | 47.39 | 50.83 | 54.31 | 57.81 | 61.32 |
| 0.90 | 22.16 | 24.58 | 27.12 | 29.82 | 32.67 | 35.67 | 38.81 | 42.06 | 45.39 | 48.79 | 52.23 | 55.71 | 59.22 | 62.74 |
| 0.95 | 24.28 | 26.70 | 29.26 | 31.97 | 34.84 | 37.85 | 41.00 | 44.26 | 47.61 | 51.02 | 54.47 | 57.95 | 61.45 | 64.97 |
| 0.98 | 27.00 | 29.43 | 31.99 | 34.71 | 37.58 | 40.61 | 43.77 | 47.04 | 50.39 | 53.80 | 57.25 | 60.74 | 64.24 | 67.76 |
| 0.99 | 29.03 | 31.46 | 34.03 | 36.75 | 39.63 | 42.66 | 45.82 | 49.09 | 52.44 | 55.85 | 59.31 | 62.79 | 66.30 | 69.81 |
| 0.995 | 31.05 | 33.48 | 36.05 | 38.77 | 41.65 | 44.69 | 47.85 | 51.12 | 54.47 | 57.89 | 61.34 | 64.83 | 68.33 | 71.85 |

h = 7,000 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 16.06 | 18.48 | 20.98 | 23.63 | 26.38 | 29.28 | 32.34 | 35.52 | 38.81 | 42.20 | 45.65 | 49.16 | 52.70 | 56.27 |
| 0.50 | 17.18 | 19.64 | 22.21 | 24.90 | 27.74 | 30.73 | 33.85 | 37.10 | 40.44 | 43.87 | 47.36 | 50.89 | 54.45 | 58.04 |
| 0.60 | 18.08 | 20.58 | 23.18 | 25.91 | 28.81 | 31.82 | 34.98 | 38.26 | 41.63 | 45.09 | 48.60 | 52.16 | 55.75 | 59.34 |
| 0.70 | 19.13 | 21.65 | 24.27 | 27.06 | 29.97 | 33.03 | 36.22 | 39.53 | 42.94 | 46.41 | 49.93 | 53.50 | 57.09 | 60.70 |
| 0.80 | 20.47 | 23.00 | 25.66 | 28.46 | 31.41 | 34.51 | 37.74 | 41.08 | 44.50 | 47.99 | 51.53 | 55.10 | 58.69 | 62.31 |
| 0.85 | 21.35 | 23.90 | 26.57 | 29.39 | 32.36 | 35.48 | 38.72 | 42.07 | 45.51 | 49.01 | 52.54 | 56.11 | 59.70 | 63.31 |
| 0.90 | 22.56 | 25.12 | 27.80 | 30.64 | 33.62 | 36.75 | 40.00 | 43.36 | 46.81 | 50.31 | 53.86 | 57.44 | 61.03 | 64.64 |
| 0.95 | 24.55 | 27.12 | 29.81 | 32.66 | 35.66 | 38.80 | 42.07 | 45.44 | 48.90 | 52.41 | 55.96 | 59.53 | 63.13 | 66.74 |
| 0.98 | 27.10 | 29.68 | 32.38 | 35.23 | 38.24 | 41.39 | 44.67 | 48.05 | 51.50 | 55.02 | 58.57 | 62.15 | 65.75 | 69.37 |
| 0.99 | 29.01 | 31.59 | 34.29 | 37.15 | 40.16 | 43.31 | 46.59 | 49.98 | 53.43 | 56.95 | 60.50 | 64.08 | 67.68 | 71.30 |
| 0.995 | 30.91 | 33.49 | 36.20 | 39.05 | 42.07 | 45.22 | 48.50 | 51.88 | 55.34 | 58.86 | 62.41 | 66.00 | 69.60 | 73.21 |

h = 8,000 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 16.79 | 19.31 | 21.96 | 24.69 | 27.58 | 30.62 | 33.76 | 37.04 | 40.42 | 43.91 | 47.46 | 51.07 | 54.72 | 58.36 |
| 0.50 | 17.84 | 20.43 | 23.10 | 25.92 | 28.88 | 31.96 | 35.17 | 38.51 | 41.95 | 45.47 | 49.05 | 52.68 | 56.34 | 60.01 |
| 0.60 | 18.70 | 21.30 | 24.03 | 26.87 | 29.86 | 32.99 | 36.25 | 39.63 | 43.10 | 46.64 | 50.23 | 53.86 | 57.51 | 61.19 |
| 0.70 | 19.68 | 22.32 | 25.06 | 27.94 | 30.97 | 34.15 | 37.44 | 40.84 | 44.34 | 47.90 | 51.50 | 55.13 | 58.79 | 62.46 |
| 0.80 | 20.94 | 23.60 | 26.36 | 29.28 | 32.34 | 35.54 | 38.86 | 42.29 | 45.80 | 49.38 | 53.00 | 56.64 | 60.30 | 63.90 |
| 0.85 | 21.75 | 24.44 | 27.23 | 30.15 | 33.22 | 36.44 | 39.78 | 43.22 | 46.73 | 50.31 | 53.93 | 57.58 | 61.25 | 64.94 |
| 0.90 | 22.91 | 25.59 | 28.38 | 31.32 | 34.41 | 37.64 | 41.00 | 44.45 | 47.97 | 51.55 | 55.18 | 58.83 | 62.50 | 66.18 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.95 | 24.78 | 27.47 | 30.28 | 33.23 | 36.33 | 39.57 | 42.93 | 46.39 | 49.93 | 53.52 | 57.15 | 60.80 | 64.47 | 68.16 |
| 0.98 | 27.19 | 29.88 | 32.69 | 35.65 | 38.76 | 42.01 | 45.38 | 46.85 | 52.39 | 55.98 | 59.61 | 63.27 | 66.94 | 70.63 |
| 0.99 | 28.98 | 31.68 | 34.50 | 37.46 | 40.57 | 43.82 | 47.19 | 50.66 | 54.20 | 57.80 | 61.43 | 65.09 | 68.76 | 72.45 |
| 0.995 | 30.77 | 33.47 | 36.29 | 39.25 | 42.36 | 45.61 | 48.99 | 52.46 | 56.00 | 59.59 | 63.23 | 66.88 | 70.56 | 74.24 |

* h = height interval (m)

TABLE 2-60. Conditional Percentiles Of Wind Speed Shear (m/s) Given Wind Speed (m/s) Applicable over The 3- to 16-Km Altitude Range, KSC, February (Continued).*

h = 9,000 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 17.54 | 20.17 | 22.86 | 25.69 | 28.64 | 31.72 | 34.95 | 38.30 | 41.76 | 45.31 | 48.92 | 52.58 | 56.27 | 60.00 |
| 0.50 | 18.57 | 21.22 | 23.98 | 26.86 | 29.87 | 33.03 | 36.33 | 39.74 | 43.24 | 46.82 | 50.46 | 54.13 | 57.84 | 61.57 |
| 0.60 | 19.38 | 22.08 | 24.86 | 27.78 | 30.85 | 34.04 | 37.36 | 40.80 | 44.33 | 47.94 | 51.61 | 55.30 | 59.00 | 62.72 |
| 0.70 | 20.34 | 23.05 | 25.86 | 28.82 | 31.90 | 35.13 | 38.49 | 41.95 | 45.51 | 49.12 | 52.79 | 56.49 | 60.22 | 63.97 |
| 0.80 | 21.54 | 24.28 | 27.13 | 30.10 | 33.22 | 36.48 | 39.87 | 43.36 | 46.93 | 50.56 | 54.23 | 57.94 | 61.67 | 65.41 |
| 0.85 | 22.35 | 25.10 | 27.95 | 30.95 | 34.08 | 37.36 | 40.75 | 44.25 | 47.83 | 51.48 | 55.16 | 58.87 | 62.59 | 66.33 |
| 0.90 | 23.45 | 26.20 | 29.07 | 32.07 | 35.22 | 38.51 | 41.92 | 45.43 | 49.02 | 52.66 | 56.35 | 60.06 | 63.79 | 67.54 |
| 0.95 | 25.25 | 28.01 | 30.89 | 33.91 | 37.07 | 40.37 | 43.79 | 47.31 | 50.91 | 54.56 | 58.25 | 61.96 | 65.70 | 69.44 |
| 0.98 | 27.56 | 30.34 | 33.22 | 36.24 | 39.41 | 42.72 | 46.15 | 49.68 | 53.28 | 56.93 | 60.62 | 64.34 | 68.07 | 71.81 |
| 0.99 | 29.29 | 32.07 | 34.95 | 37.98 | 41.15 | 44.47 | 47.90 | 51.43 | 55.03 | 58.68 | 62.37 | 66.09 | 69.82 | 73.56 |
| 0.995 | 31.02 | 33.79 | 36.68 | 39.70 | 42.88 | 46.19 | 49.63 | 53.16 | 56.76 | 60.41 | 64.10 | 67.82 | 71.55 | 75.30 |

h = 10,000 meters (W1 to W2 m/s)

| PROB | 20 25 | 25 30 | 30 35 | 35 40 | 40 45 | 45 50 | 50 55 | 55 60 | 60 65 | 65 70 | 70 75 | 75 80 | 80 85 | 85 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.36788 | 18.05 | 20.77 | 23.59 | 26.49 | 29.54 | 32.74 | 36.08 | 39.52 | 43.06 | 46.67 | 50.34 | 54.05 | 57.79 | 61.56 |
| 0.50 | 18.99 | 21.78 | 24.62 | 27.59 | 30.72 | 33.96 | 37.33 | 40.81 | 44.39 | 48.05 | 51.76 | 55.50 | 59.25 | 63.02 |
| 0.60 | 19.76 | 22.56 | 25.45 | 28.45 | 31.59 | 34.88 | 38.29 | 41.80 | 45.40 | 49.06 | 52.77 | 56.52 | 60.30 | 64.09 |
| 0.70 | 20.64 | 23.47 | 26.37 | 29.41 | 32.60 | 35.92 | 39.35 | 42.89 | 46.52 | 50.19 | 53.91 | 57.65 | 61.42 | 65.21 |
| 0.80 | 21.76 | 24.60 | 27.55 | 30.62 | 33.82 | 37.16 | 40.62 | 44.18 | 47.81 | 51.51 | 55.24 | 59.01 | 62.78 | 66.56 |
| 0.85 | 22.50 | 25.37 | 28.31 | 31.39 | 34.62 | 37.97 | 41.45 | 45.02 | 48.66 | 52.35 | 56.08 | 59.84 | 63.62 | 67.41 |
| 0.90 | 23.52 | 26.39 | 29.35 | 32.45 | 35.68 | 39.04 | 42.52 | 46.10 | 49.75 | 53.46 | 57.20 | 60.96 | 64.74 | 68.53 |
| 0.95 | 25.18 | 28.06 | 31.04 | 34.14 | 37.39 | 40.77 | 44.26 | 47.85 | 51.50 | 55.21 | 58.96 | 62.72 | 66.50 | 70.29 |
| 0.98 | 27.33 | 30.21 | 33.19 | 36.30 | 39.56 | 42.94 | 46.44 | 50.04 | 53.70 | 57.40 | 61.15 | 64.91 | 68.70 | 72.49 |
| 0.99 | 28.93 | 31.81 | 34.79 | 37.91 | 41.17 | 44.55 | 48.06 | 51.65 | 55.31 | 59.02 | 62.77 | 66.53 | 70.32 | 74.11 |
| 0.995 | 30.52 | 33.40 | 36.39 | 39.50 | 42.76 | 46.15 | 49.66 | 53.25 | 56.91 | 60.62 | 64.37 | 68.14 | 71.92 | 75.71 |

* h = height interval (m)

This conditional probability distribution function is for the given value for $Y$ equal to exactly the assigned value for $Y_1$ instead of an assigned class interval as presented in equation (2.56). An explicit inverse solution cannot be obtained to find the conditional percentile values for $X^*$ as a function of probability, $P$. If interactive techniques are used such as Newton's method to do this, care must be taken for the computational precision for small values of $Y_1$. The usual practical range for the reduced variates is from -3.5 to +5.0. The extreme wind speed shear and associated wind speed data computed from the 150 per month jimsphere samples for KSC revealed that the data for February would encompass the other months. Hence, February is used to typify these wind shear statistics. For computational conveniences, the five required parameters for the bivariate extreme value distribution were fit by empirical equations as a function of altitude shear interval, $h$, valid for $100 \le h \le 10{,}000$ m. For the extreme largest wind speed shear parameters:

$$m_s(h) = 0.4747\, h^{0.47} \text{ , } (100 \le h \le 10{,}000\, m) \tag{2.59}$$

and

$$a_s(h) = \frac{10\, h}{1{,}300 + h} \text{ , } (100 \le h \le 10{,}000\, m) \text{ .} \tag{2.60}$$

For the associated wind speed with the extreme largest wind speed shear parameters:

$$m_w(h) = 34.71 + 0.0071\, h ; \; (100 \le h \le 600\, m) \tag{2.61}$$

$$m_w(h) = 39.2936 + 0.001127\,h\,; \quad (600 < h \leq 10{,}000\,m)\ .$$

and

$$a_w(h) = 11.60 \text{ for all } h \geq 100\,m\ . \qquad (2.62)$$

The units for these parameters are m/s.

The empirical equation for the *m*-parameter is:

$$m(h) = 1.27 + 0.00026\,h\ ,\ (100 \leq h \leq 10{,}000\,m)\ . \qquad (2.63)$$

Evaluating this equation for $h$ = 100 m and $h$ = 10,000 m yields the values of 1.296 and 3.870. From equation (2.54), this gives the correlation coefficients between the extreme largest shear and associated wind speed for $h$ = 100 m as 0.4046 and for $h$ = 10,000 m as 0.9332. Hence, as the altitude shear interval increases, this correlation coefficient between the wind shear and wind speed increases.

The above empirical equations for the five bivariate extreme value distribution functions were used in equation (2.56) to establish the conditional percentile values for wind speed shear for the given wind speed class intervals shown in Table 2-60. The 99th conditional extreme value wind shear at various shear intervals, $h$, gives the associated wind speed. As shown, for the given wind speed, the conditional wind shear over large shear intervals exceeds the given wind speed. This indicates that this wind shear model is invalid in this domain.

2.3.5.3.3 <u>Percentile Values for Extreme Largest Wind Speed Shear</u>. The univariate extreme value distribution for wind speed shear can be computed using the $\mu_s(h)$ and $a_s(h)$ parameters from equations (2.59) and (2.60) in the univariate extreme value probability distribution function. The percentile values for wind speed shear versus shear intervals, $S(h;P)$, in Table 2-61, are computed from:

$$S(h;P) = m_S(h) + a_S(h)\,Y\ , \qquad (2.64)$$

where

$$Y = -ln(-ln\ P) \text{ and } P \text{ is probability.}$$

Using the same procedure, the empirical equations for $\mu_s(h)$ and $a_s(h)$ for the extreme largest wind speed shear in the 3- to 16-km altitude for KSC, July, are:

$$m_S(h) = 0.5822\,h^{0.36} \qquad (2.65)$$

and

$$a_S(h) = 0.0507\,h^{0.57}\ . \qquad (2.66)$$

The KSC February and July percentile values for the extreme largest wind speed shear are given in Tables 2-61 and 2-62, respectively. Comparing the wind shears (Tables 2-61 and 2-62) it is seen that the wind shears are greater during February than July for shear intervals, $h$, greater than 100 m. This is because the extreme largest wind profile shears are correlated with the wind speed, and as the shear interval increases the correlation increases

TABLE 2-61. Percentile Values (m/s) Versus Shear Intervals For Extreme Largest Shear (3- To 16-Km Altitude) February, KSC, FL.

| Shear Interval (m) | 36.79 | 50.00 | 60.00 | 70.00 | 80.00 | 85.00 | 90.00 | 95.00 | 98.00 | 99.00 | 99.50 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 100.0 | 4.13 | 4.40 | 4.61 | 4.87 | 5.21 | 5.43 | 5.74 | 6.26 | 6.92 | 7.42 | 7.92 |
| 200.0 | 5.73 | 6.22 | 6.62 | 7.10 | 7.73 | 8.15 | 8.73 | 9.69 | 10.93 | 11.86 | 12.79 |
| 300.0 | 6.93 | 7.62 | 8.19 | 8.86 | 9.74 | 10.34 | 11.15 | 12.50 | 14.25 | 15.55 | 16.86 |
| 400.0 | 7.93 | 8.79 | 9.51 | 10.36 | 11.46 | 12.21 | 13.23 | 14.92 | 17.11 | 18.76 | 20.39 |
| 500.0 | 8.81 | 9.83 | 10.68 | 11.67 | 12.98 | 13.86 | 15.06 | 17.06 | 19.65 | 21.59 | 23.52 |
| 600.0 | 9.60 | 10.75 | 11.72 | 12.85 | 14.33 | 15.34 | 16.70 | 18.98 | 21.92 | 24.12 | 26.32 |
| 700.0 | 10.32 | 11.60 | 12.67 | 13.93 | 15.57 | 16.68 | 18.19 | 20.71 | 23.98 | 26.42 | 28.85 |
| 800.0 | 10.99 | 12.38 | 13.55 | 14.91 | 16.70 | 17.91 | 19.56 | 22.30 | 25.85 | 28.51 | 31.16 |
| 900.0 | 11.61 | 13.11 | 14.36 | 15.83 | 17.75 | 19.05 | 20.82 | 23.76 | 27.57 | 30.43 | 33.28 |
| 1,000.0 | 12.20 | 13.80 | 15.12 | 16.68 | 18.72 | 20.10 | 21.99 | 25.12 | 29.17 | 32.20 | 35.23 |
| 1,500.0 | 14.76 | 16.73 | 18.36 | 20.29 | 22.80 | 24.50 | 26.82 | 30.68 | 35.67 | 39.41 | 43.13 |
| 2,000.0 | 16.90 | 19.12 | 20.97 | 23.15 | 25.99 | 27.91 | 30.54 | 34.90 | 40.55 | 44.78 | 49.00 |
| 2,500.0 | 18.77 | 21.18 | 23.19 | 25.55 | 28.64 | 30.72 | 33.57 | 38.31 | 44.44 | 49.03 | 53.61 |
| 3,000.0 | 20.45 | 23.01 | 25.14 | 27.64 | 30.91 | 33.13 | 36.15 | 41.17 | 47.67 | 52.54 | 57.40 |
| 3,500.0 | 21.99 | 24.66 | 26.88 | 29.50 | 32.92 | 35.23 | 38.39 | 43.64 | 50.44 | 55.53 | 60.60 |
| 4,000.0 | 23.41 | 26.18 | 28.48 | 31.19 | 34.73 | 37.12 | 40.39 | 45.83 | 52.86 | 58.13 | 63.38 |
| 5,000.0 | 26.00 | 28.91 | 31.33 | 34.18 | 37.90 | 40.42 | 43.86 | 49.57 | 56.97 | 62.51 | 68.03 |
| 6,000.0 | 28.32 | 31.34 | 33.84 | 36.80 | 40.65 | 43.26 | 46.82 | 52.74 | 60.39 | 66.13 | 71.85 |
| 7,000.0 | 30.45 | 33.54 | 36.12 | 39.15 | 43.10 | 45.78 | 49.43 | 55.50 | 63.36 | 69.25 | 75.12 |
| 8,000.0 | 32.42 | 35.58 | 38.20 | 41.29 | 45.33 | 48.05 | 51.78 | 57.97 | 65.99 | 72.00 | 77.98 |
| 9,000.0 | 34.27 | 37.47 | 40.14 | 43.28 | 47.38 | 50.15 | 53.93 | 60.22 | 68.36 | 74.47 | 80.54 |
| 10,000.0 | 36.01 | 39.25 | 41.95 | 45.13 | 49.28 | 52.09 | 55.92 | 62.29 | 70.54 | 76.72 | 82.88 |

TABLE 2-62. Percentile Values (m/s) Versus Shear Intervals For Extreme Largest Wind Shear (3- To 16-Km Altitude) July, KSC, FL.

| Shear Interval (m) | 36.79 | 50.00 | 60.00 | 70.00 | 80.00 | 85.00 | 90.00 | 95.00 | 98.00 | 99.00 | 99.50 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 100.0 | 3.06 | 3.31 | 3.53 | 3.78 | 4.11 | 4.33 | 4.63 | 5.13 | 5.79 | 6.27 | 6.76 |
| 200.0 | 3.92 | 4.30 | 4.62 | 4.99 | 5.48 | 5.81 | 6.26 | 7.01 | 7.98 | 8.70 | 9.42 |
| 300.0 | 4.54 | 5.02 | 5.42 | 5.89 | 6.50 | 6.92 | 7.48 | 8.43 | 9.65 | 10.56 | 11.47 |
| 400.0 | 5.03 | 5.60 | 6.07 | 6.62 | 7.35 | 7.84 | 8.50 | 9.61 | 11.05 | 12.13 | 13.20 |
| 500.0 | 5.45 | 6.10 | 6.63 | 7.26 | 8.08 | 8.64 | 9.40 | 10.66 | 12.29 | 13.51 | 14.73 |
| 600.0 | 5.82 | 6.54 | 7.13 | 7.83 | 8.74 | 9.35 | 10.20 | 11.60 | 13.41 | 14.76 | 16.12 |
| 700.0 | 6.16 | 6.93 | 7.58 | 8.34 | 9.34 | 10.01 | 10.93 | 12.46 | 14.44 | 15.92 | 17.39 |
| 800.0 | 6.46 | 7.30 | 8.00 | 8.82 | 9.89 | 10.62 | 11.61 | 13.26 | 15.39 | 16.99 | 18.58 |
| 900.0 | 6.74 | 7.64 | 8.38 | 9.26 | 10.41 | 11.19 | 12.25 | 14.01 | 16.29 | 18.00 | 19.71 |
| 1,000.0 | 7.00 | 7.95 | 8.75 | 9.68 | 10.90 | 11.72 | 12.85 | 14.72 | 17.15 | 18.96 | 20.77 |
| 1,500.0 | 8.10 | 9.30 | 10.30 | 11.48 | 13.01 | 14.05 | 15.47 | 17.83 | 20.88 | 23.17 | 25.45 |
| 2,000.0 | 8.98 | 10.40 | 11.58 | 12.96 | 14.77 | 16.00 | 17.67 | 20.45 | 24.05 | 26.74 | 29.43 |
| 2,500.0 | 9.74 | 11.34 | 12.68 | 14.25 | 16.31 | 17.70 | 19.60 | 22.76 | 26.84 | 29.90 | 32.95 |
| 3,000.0 | 10.40 | 12.18 | 13.66 | 15.41 | 17.69 | 19.23 | 21.34 | 24.84 | 29.37 | 32.77 | 29.37 |
| 3,500.0 | 10.99 | 12.93 | 14.56 | 16.46 | 18.95 | 20.64 | 22.94 | 26.76 | 31.71 | 35.42 | 39.11 |
| 4,000.0 | 11.53 | 13.63 | 15.38 | 17.44 | 20.12 | 21.94 | 24.43 | 28.55 | 33.89 | 37.89 | 41.88 |
| 5,000.0 | 12.49 | 14.88 | 16.87 | 19.20 | 22.26 | 24.32 | 27.14 | 31.82 | 37.89 | 42.43 | 46.96 |
| 6,000.0 | 13.34 | 15.99 | 18.19 | 20.79 | 24.17 | 26.46 | 29.59 | 34.79 | 41.51 | 46.56 | 51.58 |
| 7,000.0 | 14.10 | 16.99 | 19.40 | 22.23 | 25.93 | 28.43 | 31.84 | 37.52 | 44.86 | 50.37 | 55.85 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 8,000.0 | 14.80 | 17.92 | 20.51 | 23.57 | 27.56 | 30.25 | 33.94 | 40.06 | 47.99 | 53.93 | 59.85 |
| 9,000.0 | 15.44 | 18.77 | 21.55 | 24.82 | 29.08 | 31.97 | 35.91 | 42.46 | 50.94 | 57.29 | 63.63 |
| 10,000.0 | 16.04 | 19.58 | 22.52 | 25.99 | 30.53 | 33.59 | 37.78 | 44.73 | 53.73 | 60.48 | 67.20 |

2.3.5.3.4 Percentile Values for Extreme Largest Wind Speed. An estimate for the extreme value pdf for the extreme largest wind speed in the 3- to 16-km layer can be obtained by evaluating equations (2.49) and (2.50) at the shear interval $h$ = 10,000 m for the parameters $m_w$ and $\alpha_w$. For KSC February, this gives $m_w$ = 50.56 m/s and $\alpha_w$ = 11.60 m/s. The percentile values for the extreme largest wind speed is then estimated by:

$$W(P) = 50.56+11.60Y \ , \qquad (2.67)$$

where

$Y = -ln(-ln\ P)$ , and $P$ is probability.

TABLE 2-63. Comparison of Some Wind Speed Percentile Values, KSC.

| Probability (Percent) | Scalar Wind Speed (a) (m/s) | Extreme Wind Speed (b) (m/s) | Largest $u$-Component (c) (m/s) |
|---|---|---|---|
| 50 | 45 | 54.8 | 49.8 |
| 75 | 57 | 65.0 | 68.1 |
| 80 | 68 | 68.0 | 71.0 |
| 95 | 75 | 85.0 | 85.8 |
| 99 | 92 | 103.9 | 99.1 |

(a) From Table 2-49, empirical monthly envelope for percentile values at 12-km altitude.

(b) Estimated from equation (2.67), February.

(c) The largest zonal wind component to probability ellipses using monthly enveloping bivariate normal parameters at 12-km altitude presented later in Table 2-74. At 12-km altitude,

$u_A$ = 30.34 m/s and $s_{Au}$ = 22.67 m/s, $u_L = u_A + s_{Au}\ \lambda e$, where $\lambda e = \sqrt{-2\,ln(1-p)}$.

Considering that the wind speed percentile values in Table 2-63 are derived from three different methods and three different data bases, the agreement is remarkably close.

2.3.6 Wind Speed Change Envelopes. This section provides representative information on wind speed change (shear) for scales of distance $\Delta H \leq$ 5,000 m. Wind speed change is defined as the total magnitude (speed) change between the wind vector at the top and bottom of a specified layer, regardless of wind direction. Wind shear is defined as the wind speed change divided by the altitude interval. When applied to aerospace vehicle synthetic profile criteria, it is frequently referred to as a wind buildup or back-off rate depending upon whether it occurs below (buildup) or above (back-off) the reference height of concern. Thus, a buildup wind value is the change in wind speed which a vehicle may experience while ascending vertically through a specified layer to the known altitude. Back-off magnitudes describe the speed change which may be experienced above the chosen level. Both buildup and back-off wind speed change data are presented in this section as a function of reference level wind vector magnitude and geographical location. Wind buildup or back-off may be determined for a vehicle with other than a vertical flight path by multiplying the wind speed change by the cosine of the angle between the vertical axis and the vertical trajectory. Wind shears for scales of distance $\Delta H \geq$ 1,000 m thickness are computed from rawinsonde and rocketsonde observations, while the small-scale shears associated with scales of distance $\Delta H \leq$ 1,000 m are computed from a relationship developed by Fichtl (Ref. 2-39) based on experimental results from FPS-16 radar/jimsphere balloon wind sensor measurements of the detail wind profile structure. This relationship states that the back-off or buildup wind shear $\Delta u$ for $\Delta H$ < 1,000 m for a given risk of exceedance is related to the $\Delta H$ = 1,000 m shear, $(\Delta u)_{1,000}$, at the same risk of exceedance, through the expression

$$\Delta u = (\Delta u)_{1,000} \left( \frac{\Delta H}{1{,}000} \right)^{0.7} , \qquad (2.68)$$

where $\Delta H$ has the units of meters. Equation (2.68) was used to construct Tables 2-64 to 2-73 for scales of distance $\leq$ 1,000 m.

An envelope of the 99-percentile wind speed buildup is used currently in constructing synthetic wind profiles. For most design studies, the use of this 99-percent scalar buildup wind shear data is warranted. The envelopes for back-off shears have application to certain design studies and should be considered where appropriate. These envelopes are not meant to imply perfect correlation between shears for the various scales of distance; however, certain correlations do exist, depending upon the scale of distance and the wind speed magnitude considered. This method of describing the wind shear for vehicle design has proven to be especially acceptable in preliminary design studies since the dynamic response of the structure or control system of a vehicle is essentially influenced by specific wavelengths as represented by a given wind shear. Construction of synthetic profiles for vehicle design applications is described in section 2.3.9.

Wind speed change (shear) statistics for various locations differ primarily because of prevailing meteorological conditions, orographic features, and data sample size. Significant differences, especially from an engineering standpoint, are known to exist in the shear profiles for different locations. Therefore, consistent vehicle design shear data (99-percentile) representing four active or potentially operational space vehicle launch or landing sites are presented in Tables 2-64 through 2-71; i.e., for KSC, VAFB, White Sands Missile Range, and EAFB. Tables 2-72 and 2-73 envelope the 99-percentile shears from these four locations. They are applicable for design criteria when initial design or operational capability has not been restricted to a specific launch site or may involve several geographical locations. However, if the specific geographic location for application has been determined as being near one of the four referenced sites, then the relevant data should be applied.

2.3.7 Wind Direction Change Envelopes. This section provides representative information on wind direction change $\Delta q$ for scales of distance $\Delta H \leq 4$ km. Wind direction change is defined as the total change in direction of wind vectors at the top and bottom of a specified layer. Wind direction changes can occur above or below a reference point in the atmosphere. As in the case of the wind speed changes in section 2.3.6, we will call changes below the reference level buildup wind changes and those above the reference level back-off wind direction changes. These changes can be significantly different. For example, if the reference point is at the 4-km level, the buildup changes between the 1- and 4-km levels will be distinctly different from the back-off changes between the 5- to 7-km levels. This results from the fact that variations of wind direction tend to be larger in the atmospheric boundary layer. In this light, the following model is recommended as an integrated wind direction change criterion for design studies. The model consists of the 8- to 16-km 99-percent direction changes in figure 2-20 and a set of functions $R(\Delta H, H_r, u_r)$ to transfer these changes to any reference level $H_r$ above the 1-km level, where $u_r$ is the reference level wind speed.

TABLE 2-64. Buildup Design Envelopes of 99-Percentile Wind Speed Change (m/s), 1- To 80-Km Reference Altitude Region, KSC.

| | Altitude Interval (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) at Reference Altitude | 5,000 | 4,000 | 3,000 | 2,000 | 1,000 | 800 | 600 | 400 | 200 | 100 |
| $\geq$ 90 | 65.6 | 59.5 | 52.3 | 43.5 | 34.0 | 29.0 | 23.8 | 17.9 | 11.2 | 6.8 |
| = 80 | 60.4 | 55.5 | 49.7 | 42.0 | 32.7 | 27.7 | 22.7 | 17.0 | 10.6 | 6.5 |
| = 70 | 56.0 | 51.7 | 47.0 | 40.4 | 31.2 | 26.6 | 21.8 | 16.4 | 10.1 | 6.2 |
| = 60 | 51.3 | 48.5 | 44.5 | 38.6 | 30.0 | 25.6 | 21.1 | 15.8 | 9.8 | 6.0 |
| = 50 | 46.5 | 45.0 | 41.2 | 36.5 | 28.5 | 24.4 | 20.0 | 15.0 | 9.2 | 5.7 |
| = 40 | 38.5 | 37.7 | 36.8 | 34.9 | 26.5 | 22.6 | 18.5 | 13.8 | 8.6 | 5.3 |
| = 30 | 28.0 | 27.5 | 26.5 | 24.5 | 20.8 | 17.8 | 14.5 | 10.8 | 6.7 | 4.1 |
| = 20 | 17.6 | 17.3 | 16.6 | 15.8 | 14.6 | 12.5 | 10.2 | 7.2 | 4.7 | 2.9 |

TABLE 2-65. Back-Off Design Envelopes of 99-Percentile Wind Speed Change (m/s), 1- To 80-Km Reference Altitude Region, KSC.

| | Altitude Interval (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) at Reference Altitude | 5,000 | 4,000 | 3,000 | 2,000 | 1,000 | 800 | 600 | 400 | 200 | 100 |
| $\geq$ 90 | 77.5 | 74.4 | 68.0 | 59.3 | 42.6 | 36.4 | 29.7 | 22.4 | 13.8 | 8.5 |
| = 80 | 71.0 | 68.0 | 63.8 | 56.0 | 40.5 | 34.7 | 28.5 | 21.4 | 13.2 | 8.1 |
| = 70 | 63.5 | 61.0 | 57.9 | 52.0 | 38.8 | 33.1 | 27.0 | 20.3 | 12.5 | 7.7 |
| = 60 | 56.0 | 54.7 | 52.3 | 47.4 | 36.0 | 31.0 | 25.3 | 18.9 | 11.7 | 7.2 |
| = 50 | 47.5 | 47.0 | 46.2 | 43.8 | 33.0 | 28.3 | 23.2 | 17.5 | 10.7 | 6.6 |
| = 40 | 39.0 | 38.0 | 37.0 | 35.3 | 29.5 | 25.3 | 20.6 | 15.5 | 9.6 | 5.9 |
| = 30 | 30.0 | 30.0 | 29.4 | 26.9 | 22.6 | 19.4 | 15.8 | 11.9 | 7.3 | 4.5 |
| = 20 | 18.0 | 17.5 | 16.7 | 15.7 | 14.2 | 12.2 | 9.9 | 7.5 | 4.6 | 2.8 |

TABLE 2-66. Buildup Design Envelopes Of 99-Percentile Wind Speed Change (m/s), 1- To 80-Km Reference Altitude Region, VAFB.

| | Altitude Interval (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) at Reference Altitude | 5,000 | 4,000 | 3,000 | 2,000 | 1,000 | 800 | 600 | 400 | 200 | 100 |
| $\geq$ 90 | 62.1 | 59.9 | 57.8 | 51.5 | 35.2 | 30.1 | 24.6 | 18.4 | 11.5 | 7.0 |
| = 80 | 58.7 | 57.7 | 55.6 | 48.8 | 33.5 | 29.0 | 23.6 | 17.8 | 11.0 | 6.7 |
| = 70 | 55.0 | 54.5 | 53.4 | 48.1 | 33.0 | 28.8 | 23.0 | 16.8 | 10.5 | 6.5 |
| = 60 | 50.4 | 49.9 | 49.0 | 44.0 | 32.7 | 27.9 | 22.8 | 16.2 | 9.7 | 5.3 |
| = 50 | 45.4 | 44.8 | 43.7 | 40.0 | 29.9 | 25.4 | 21.8 | 15.6 | 9.2 | 5.0 |
| = 40 | 38.9 | 38.7 | 37.2 | 34.9 | 25.1 | 22.4 | 19.1 | 14.9 | 8.8 | 4.7 |
| = 30 | 30.0 | 29.4 | 28.3 | 25.4 | 19.9 | 17.8 | 14.8 | 11.5 | 7.1 | 4.2 |
| = 20 | 20.0 | 19.8 | 19.5 | 18.4 | 15.0 | 13.1 | 10.9 | 8.0 | 4.7 | 2.6 |

TABLE 2-67. Back-Off Design Envelopes of 99-Percentile Wind Speed Change (m/s), 1- To 80-Km Reference Altitude Region, VAFB.

| | Altitude Interval (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) at Reference Altitude | 5,000 | 4,000 | 3,000 | 2,000 | 1,000 | 800 | 600 | 400 | 200 | 100 |
| ≥ 90 | 66.9 | 62.5 | 57.7 | 49.9 | 37.5 | 32.1 | 26.1 | 19.7 | 12.0 | 7.4 |
| = 80 | 64.1 | 60.8 | 56.6 | 48.3 | 36.9 | 31.5 | 25.6 | 19.1 | 11.6 | 6.8 |
| = 70 | 62.0 | 59.2 | 54.8 | 47.1 | 36.0 | 31.0 | 25.0 | 18.6 | 11.2 | 6.5 |
| = 60 | 57.1 | 54.5 | 51.3 | 45.4 | 32.6 | 28.5 | 23.0 | 17.1 | 10.2 | 5.3 |
| = 50 | 49.6 | 47.8 | 45.7 | 42.1 | 30.1 | 25.9 | 20.8 | 15.5 | 9.2 | 5.0 |
| = 40 | 39.4 | 38.8 | 37.9 | 35.5 | 25.9 | 23.5 | 19.6 | 14.0 | 8.2 | 4.8 |
| = 30 | 29.9 | 29.3 | 28.3 | 26.3 | 20.5 | 18.6 | 15.8 | 12.2 | 8.0 | 4.6 |
| = 20 | 19.8 | 19.5 | 19.0 | 17.7 | 13.4 | 12.2 | 10.7 | 9.0 | 6.3 | 4.3 |

TABLE 2-68. Buildup Design Envelopes of 99-Percentile Wind Speed Change (m/s), 1- To 80-Km reference Altitude Region, White Sands Missile Range.

| | Altitude Interval (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) at Reference Altitude | 5,000 | 4,000 | 3,000 | 2,000 | 1,000 | 800 | 600 | 400 | 200 | 100 |
| ≥ 90 | 70.7 | 67.0 | 61.2 | 52.4 | 42.0 | 36.0 | 29.4 | 22.1 | 13.6 | 8.4 |
| = 80 | 66.0 | 63.0 | 57.7 | 50.0 | 40.2 | 34.5 | 28.1 | 21.2 | 13.0 | 8.0 |
| = 70 | 60.2 | 57.0 | 53.0 | 46.5 | 38.0 | 32.6 | 26.6 | 20.0 | 12.3 | 7.6 |
| = 60 | 52.4 | 50.0 | 46.5 | 42.3 | 35.5 | 30.5 | 24.9 | 18.7 | 11.5 | 7.1 |
| = 50 | 44.8 | 43.0 | 40.2 | 36.5 | 32.0 | 28.3 | 23.1 | 17.4 | 10.7 | 6.6 |
| = 40 | 36.4 | 35.3 | 33.8 | 31.0 | 27.5 | 23.6 | 19.3 | 14.5 | 8.9 | 5.5 |
| = 30 | 27.4 | 26.5 | 25.6 | 24.3 | 20.6 | 17.7 | 14.4 | 10.8 | 6.7 | 4.1 |
| = 20 | 18.4 | 17.7 | 17.3 | 16.5 | 15.0 | 12.9 | 10.5 | 7.9 | 4.9 | 3.0 |

TABLE 2-69. Back-Off Design Envelopes Of 99-Percentile Wind Speed Change (m/s) 1- to 80-Km reference Altitude Region, White Sands Missile Range.

| | Altitude Interval (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) at Reference Altitude | 5,000 | 4,000 | 3,000 | 2,000 | 1,000 | 800 | 600 | 400 | 200 | 100 |
| ≥ 90 | 66.2 | 62.0 | 57.0 | 50.0 | 37.0 | 31.7 | 25.9 | 19.5 | 12.0 | 7.4 |
| = 80 | 62.0 | 58.5 | 54.0 | 48.0 | 35.8 | 30.7 | 25.1 | 18.9 | 11.6 | 7.1 |
| = 70 | 57.5 | 54.5 | 50.7 | 44.3 | 34.2 | 29.3 | 23.9 | 18.0 | 11.1 | 6.8 |
| = 60 | 52.6 | 49.2 | 45.5 | 40.5 | 32.8 | 28.1 | 23.0 | 17.3 | 10.6 | 6.5 |
| = 50 | 45.0 | 42.8 | 40.1 | 37.0 | 31.0 | 26.6 | 21.7 | 16.3 | 10.0 | 6.2 |
| = 40 | 36.5 | 35.5 | 34.8 | 33.5 | 29.3 | 25.1 | 20.5 | 15.4 | 9.5 | 5.8 |
| = 30 | 27.4 | 27.0 | 26.4 | 24.8 | 22.0 | 19.3 | 15.8 | 11.8 | 7.3 | 4.5 |
| = 20 | 17.7 | 17.3 | 16.7 | 15.8 | 14.1 | 12.1 | 9.9 | 7.4 | 4.6 | 2.8 |

TABLE 2-70. Buildup Design Envelopes of 99-Percentile Wind Speed Change (m/s), 1- To 80-Km Reference Altitude Region, EAFB.

| | Altitude Interval (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) at Reference Altitude | 5,000 | 4,000 | 3,000 | 2,000 | 1,000 | 800 | 600 | 400 | 200 | 100 |
| ≥ 90 | 69.0 | 65.0 | 59.5 | 52.0 | 39.5 | 33.9 | 27.7 | 20.8 | 12.8 | 7.9 |
| = 80 | 64.9 | 61.8 | 56.9 | 50.0 | 38.2 | 32.8 | 26.7 | 20.1 | 12.4 | 7.6 |
| = 70 | 59.0 | 57.0 | 53.0 | 46.8 | 37.0 | 31.7 | 25.9 | 19.5 | 12.0 | 7.4 |
| = 60 | 51.8 | 50.4 | 47.8 | 43.6 | 35.5 | 30.5 | 24.9 | 18.7 | 11.5 | 7.1 |
| = 50 | 44.8 | 43.6 | 41.3 | 38.2 | 31.8 | 27.5 | 22.4 | 16.9 | 10.4 | 6.4 |
| = 40 | 36.5 | 35.5 | 34.3 | 32.0 | 26.5 | 23.0 | 18.8 | 14.1 | 8.7 | 5.3 |
| = 30 | 28.0 | 27.3 | 26.3 | 24.5 | 20.8 | 17.8 | 14.6 | 11.0 | 6.7 | 4.2 |
| = 20 | 18.0 | 17.7 | 17.4 | 16.7 | 15.2 | 13.0 | 10.6 | 8.0 | 4.9 | 3.0 |

TABLE 2-71. Back-Off Design Envelopes of 99-Percentile Wind Speed Change (m/s), 1- To 80-Km Reference Altitude Region, EAFB.

| | Altitude Interval (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) at Reference Altitude | 5,000 | 4,000 | 3,000 | 2,000 | 1,000 | 800 | 600 | 400 | 200 | 100 |
| ≥ 90 | 75.2 | 72.0 | 67.3 | 59.0 | 42.8 | 36.7 | 30.2 | 22.5 | 13.9 | 8.5 |
| = 80 | 68.0 | 66.3 | 62.5 | 55.5 | 40.8 | 35.0 | 28.6 | 21.5 | 13.2 | 8.1 |
| = 70 | 60.4 | 59.0 | 56.8 | 51.4 | 38.7 | 33.2 | 27.0 | 20.4 | 12.5 | 7.7 |
| = 60 | 53.0 | 51.8 | 49.3 | 45.0 | 36.0 | 30.9 | 25.2 | 19.0 | 11.7 | 7.2 |
| = 50 | 44.5 | 43.3 | 41.5 | 38.4 | 32.0 | 27.5 | 22.4 | 16.9 | 10.4 | 6.4 |
| = 40 | 35.7 | 35.3 | 34.5 | 33.0 | 27.0 | 23.2 | 18.9 | 14.2 | 8.8 | 5.4 |
| = 30 | 27.1 | 27.0 | 26.9 | 26.3 | 21.4 | 18.4 | 15.0 | 11.3 | 6.9 | 4.3 |
| = 20 | 18.0 | 17.0 | 16.6 | 15.7 | 14.2 | 12.2 | 9.9 | 7.5 | 4.6 | 2.8 |

TABLE 2-72. Buildup Design Envelopes Of 99-Percentile Wind Speed Change (m/s), 1- To 80-Km Reference Altitude Region, For All Four Locations.

| | Altitude Interval (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) at Reference Altitude | 5,000 | 4,000 | 3,000 | 2,000 | 1,000 | 800 | 600 | 400 | 200 | 100 |
| ≥ 90 | 71.0 | 67.0 | 61.2 | 52.4 | 42.0 | 36.0 | 29.4 | 22.1 | 13.6 | 8.4 |
| = 80 | 66.5 | 63.0 | 57.7 | 50.0 | 40.2 | 34.5 | 28.1 | 21.2 | 13.0 | 8.0 |
| = 70 | 61.2 | 58.5 | 53.8 | 48.1 | 38.0 | 32.6 | 26.6 | 20.0 | 12.3 | 7.6 |
| = 60 | 54.4 | 52.5 | 50.0 | 44.2 | 35.5 | 30.5 | 24.9 | 18.7 | 11.5 | 7.1 |
| = 50 | 46.5 | 45.0 | 43.7 | 40.0 | 33.0 | 28.3 | 23.2 | 17.4 | 10.7 | 6.6 |
| = 40 | 38.9 | 38.7 | 37.2 | 34.9 | 27.6 | 23.7 | 19.3 | 14.9 | 8.9 | 5.5 |
| = 30 | 30.0 | 29.4 | 28.3 | 25.4 | 20.8 | 17.8 | 14.8 | 11.5 | 7.1 | 4.2 |
| = 20 | 20.0 | 19.8 | 19.5 | 18.4 | 15.2 | 13.1 | 10.9 | 8.0 | 4.9 | 3.0 |

TABLE 2-73. Back-Off Design Envelopes of 99-Percentile Wind Speed Change (m/s), 1- To 80-Km Reference Altitude Region, For All Four Locations.

| | Altitude Interval (m) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) at Reference Altitude | 5,000 | 4,000 | 3,000 | 2,000 | 1,000 | 800 | 600 | 400 | 200 | 100 |
| ≥ 90 | 77.5 | 74.4 | 68.0 | 59.3 | 42.8 | 36.7 | 30.2 | 22.5 | 13.9 | 8.5 |
| = 80 | 71.0 | 68.0 | 63.8 | 56.0 | 40.8 | 35.0 | 28.6 | 21.5 | 13.2 | 8.1 |
| = 70 | 63.5 | 61.0 | 57.9 | 52.0 | 38.8 | 33.2 | 27.0 | 20.4 | 12.5 | 7.7 |
| = 60 | 57.1 | 54.7 | 52.3 | 47.4 | 36.0 | 31.0 | 25.3 | 19.0 | 11.7 | 7.2 |
| = 50 | 49.6 | 47.8 | 46.2 | 43.8 | 33.0 | 28.3 | 23.2 | 17.5 | 10.7 | 6.6 |
| = 40 | 39.4 | 38.8 | 37.9 | 35.5 | 29.5 | 25.3 | 20.6 | 15.5 | 9.6 | 5.9 |
| = 30 | 30.0 | 30.0 | 29.4 | 26.9 | 22.6 | 19.4 | 15.8 | 12.2 | 7.3 | 4.6 |
| = 20 | 19.8 | 19.5 | 19.0 | 17.7 | 14.2 | 12.2 | 10.7 | 9.0 | 6.3 | 4.3 |

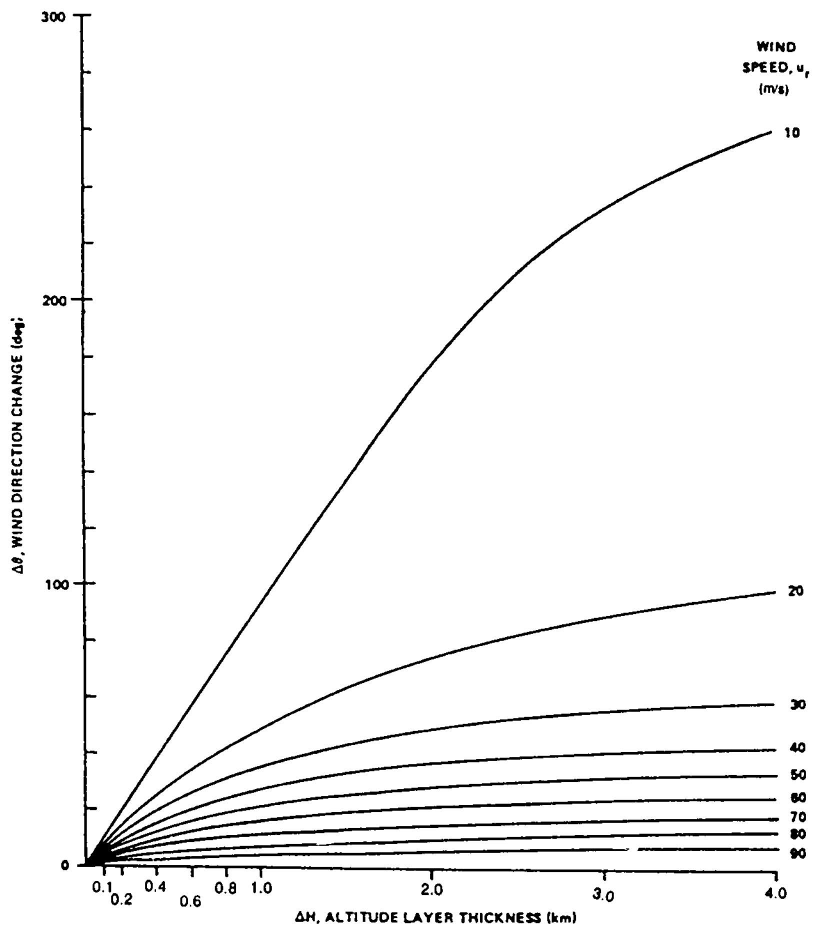



FIGURE 2-20 Idealized 99-Percent Wind Direction Change As A Function Of Wind Speed For Varying Layers In The 8- To 16-Km Altitude Region Of KSC.

The quantity $R$ is defined such that multiplication of the 8- to 16-km wind direction changes by $R(\Delta H, H_r, u_r)$ will yield the changes in wind direction over a layer of thickness $\Delta H$ with top or bottom of the reference level located at height $H_r$ above sea level and reference level wind speed equal to $u_r$. The functions $R(\Delta H, H_r, u_r)$ for back-off and buildup wind direction changes are defined as

Back-off:

$$R = R^* \; , \qquad 1 \le H_r < 1.5 \text{ km}$$

$$R = 2(1 - R^*)(H_r - 1.5) + R^* \; , \qquad 1.5 \le H_r < 2 \text{ km}$$

$$R = 1 \qquad 2 \text{ km} \le H_r \; .$$

Buildup:

$$R = R^* \; , \qquad 0 < H_r \le 2 \text{ km}$$

$$\left.\begin{array}{l} R = \left[\dfrac{R^* - 1}{2}\right][1 - \cos p\,(\Delta H - H_r + 3)] + 1 \; , \; 1 < \Delta H \le H_r - 2 \\ R = R^* \; , H_r - 2 < \Delta H \le H_r \end{array}\right\} , \qquad 2 < H_r \le 3 \text{ km}$$

$$\left.\begin{array}{l} R = 1 \, , \; 0 < \Delta H \le H_r - 3 \text{ km} \\ R = \left[\dfrac{R^* - 1}{2}\right][1 - \cos p\,(\Delta H - H_r + 3)] + 1 \; , \; H_r - 3 < \Delta H \le H_r - 2 \\ R = R^* \; , H_r - 2 < \Delta H \le 4 \text{ km} \end{array}\right\} , \qquad 3 < H_r \le 6 \text{ km}$$

$$R = 1 \; , \qquad 6 \text{ km} \le H_r \, ,$$

where $\Delta H$ and $H_r$ have units of kilometers and $R$ is a non-dimensional quantity. The quantity $R^*$ is a function of $\Delta H$ and $u_r$ and is given in figure 2-21.

To apply these wind direction change data, one first constructs a synthetic wind profile (see subsection 2.3.9), wind profile envelopes, and wind speed envelopes, with or without gust (see subsection 2.3.8), as the case may be. A reference point is selected at height $H_r$ above sea level on this synthetic wind profile. One then turns the wind direction above or bebw this point according to the schedule of wind direction changes given by the preceding model. Thus, for example, if the 12-km reference point wind speed and direction are 20 m $s^{-1}$ and 90º (east wind, i.e., a wind blowing from the east), then according to the wind direction change model discussed previously the wind directions at 0.2, 0.6, 1.0, 2.0, 3.0, and 4.0 km below or above the 12-km reference point, as the case may be, are 107º, 123º, 140º, 165º, 180º, and 190º for clockwise turning of the wind vector starting with the reference point wind vector at 12 km and looking toward the Earth. Counterclockwise turning is also permissible. The direction of rotation of the wind vector should be selected to produce the most adverse wind situation from a vehicle response point of view.

In view of the unavailability of wind direction change statistics above the 16-km level, at this time, it is recommended that the preceding procedure be used for $H_r > 16$ km.

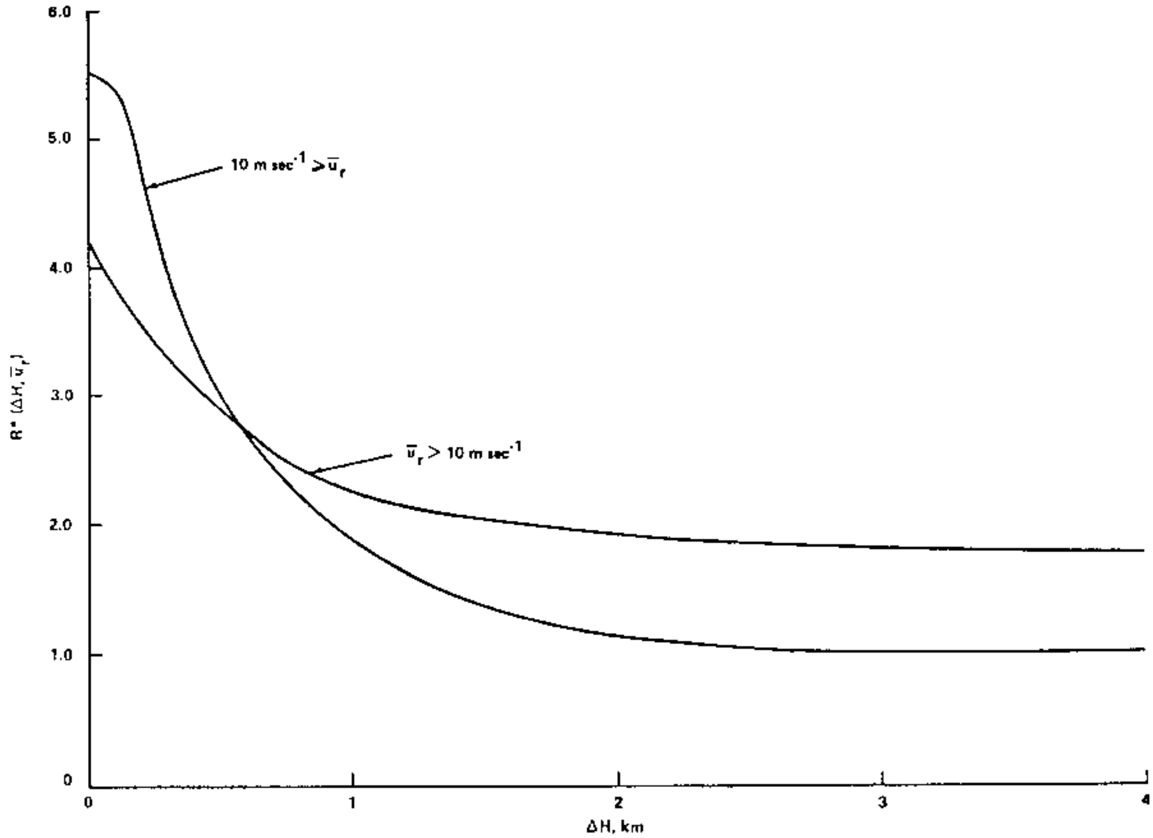



FIGURE 2-21. The Function $R^*$ Versus $\Delta H$ For Various Categories of Wind Speed $\overline{u}_r$ at The Reference Level.

2.3.8 Gusts-Vertically Flying Vehicles. The steady-state in-flight wind speed envelopes presented in section 2.3.5 do not contain the gust (high frequency content) portion of the wind profile. The steady-state wind profile measurements have been defined as those obtained by the rawinsonde system. These measurements represent wind speeds averaged over approximately 1,000 m in the vertical and, therefore, eliminate features with smaller scales. These smaller scale features are contained in the detailed profiles measured by the FPS-16 radar/jimsphere system.

A number of attempts have been made to represent the high frequency content of vertical profiles of wind in a suitable form for use in vehicle design studies. Most of the attempts resulted in gust information that could be used for specific applications, but, to date, no universal gust representation has been formulated. Information on discrete and continuous gust representations is given below relative to vertically ascending aerospace vehicles.

2.3.8.1 Discrete Gusts. Discrete gusts are specified in an attempt to represent, in a physically reasonable manner, characteristics of small-scale motions associated with vertical profiles of wind velocity. Gust structure usually is quite complex and it is not always understood. For vehicle design studies, discrete gusts are usually idealized because of their complexity and to enhance their utilization.

Well-defined, sharp-edged, and repeated sinusoidal gusts are important types in terms of their influence upon space vehicles. Quasi-square-wave gusts with amplitudes of approximately 9 m/s have been estimated as extreme gusts, and have been used in various NASA aerospace vehicle design studies. These gusts are frequently referred to as embedded jets or singularities in the vertical profile wind. By definition, a gust is a wind speed in excess of the defined steady-state value; therefore, these gusts are employed on top of the steady-state wind profile values.

If a design wind speed profile envelope without a wind shear envelope is to be used in a design study, it is recommended that the associated discrete gust vary in length from 60 to 300 m. The leading and trailing edge should conform to a 1-cosine buildup of 30 m and corresponding decay also over 30 m, as shown in figure 2-22. The plateau region of the gust can vary in thickness from zero to 240 m. An analytical expression for the value of this gust of height $H$ above natural grade is given by

$$u_g = \frac{A}{2}\left\{1-\cos\left[\frac{\pi}{30}(H-H_b)\right]\right\} \ , \ H_b \le H \le H_b+30\,\mathrm{m} \ ,$$

$$u_g = A \ , \ H_b+30\,\mathrm{m} \le H \le H_b+l-30\,\mathrm{m} \ , \qquad (2.69)$$

$$u_g = \frac{A}{2}\left\{1-\cos\left[\frac{\pi}{30}(H-H_b-l)\right]\right\} \ , \ H_b+l-30\,\mathrm{m} \le H \le H_b+l \ ,$$

where $H_b$ is the height of the base of the gust above natural grade, $l$ is the gust thickness ($60 \le l \le 300$ m), $A$ is the gust amplitude, and $MKS$ units are understood.

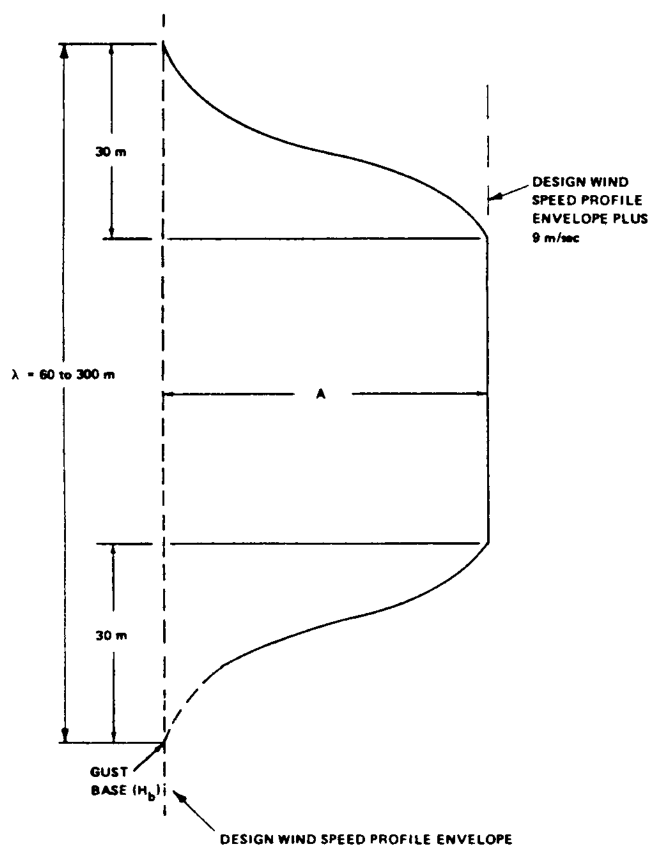


FIGURE 2-22. Relationship Between Discrete Gust and/or Embedded Jet Characteristics (Quasi-Square-Wave Shape) and the Design Wind Speed Profile Envelope.

The gust amplitude is a function of $H_b$, and, for design purposes, the 1-percent risk gust amplitude is given by

$$A = 6 \text{ m/s} \;,\quad H_b < 300 \text{ m}$$

$$A = \frac{3}{700}(H_b - 300) + 6 \;,\; 300\,\text{m} \le H_b \le 1{,}000\,\text{m} \tag{2.70}$$

$$A = 9 \text{ m/s}^{-1} \;,\quad 1{,}000 \text{ m} < H_b \;.$$

If a wind speed profile envelope with a buildup wind shear envelope (section 2.3.6) is to be used in a design study, it is recommended that the previously mentioned discrete gust be modified by replacing the leading edge 1-cosine shape with the following formula

$$u_g = 10\,A\left\{\left(\frac{H - H_b}{30}\right)^{0.9} - 0.9\left(\frac{H - H_b}{30}\right)\right\} \;,\; H_b \le H \le H_b + 30\,\text{m} \;. \tag{2.71}$$

The height of the gust base $H_b$ corresponds to the point where the design wind speed profile envelope intersects the design buildup shear envelope. If a discrete gust is to be used with a back-off wind shear envelope, then the 1-cosine trailing edge shall be given by

$$u_g = 10\,A\left\{\left(\frac{H_b + l - H}{30}\right)^{0.9} - 0.9\left(\frac{H_b + l - H}{30}\right)\right\} \;,\; H_b + l - 30\,\text{m} \le h \le H_b + l \;, \tag{2.72}$$

and the leading edge shall conform to a 1-cosine shape. In this case, the height, $H_b + l$, of the end of the gust corresponds to the point where the design wind speed profile envelope intersects the design back-off shear envelope. This modification of the 1-cosine shape at the leading and trailing edges, as the case may be, results in a continuous merger of the shear envelope and the discrete gust and shear should be reduced to 0.85 of the original value to account for the nonperfect correlation between wind shears and gusts (section 2.3.9.2 gives details).

2.3.8.1.1 Sinusoidal Gust. Another form of discrete gust that has been observed is approximately sinusoidal in nature, where gusts occur in succession. Figure 2-23 illustrates the estimated number of consecutive approximately sinusoidal type gusts that may occur and their respective amplitudes for design purposes. It is extremely important when applying these gusts in vehicle studies to realize that these are pure, mathematical sinusoidal representations that are an over-simplification of what has been observed in nature. These gusts should be superimposed symmetrically upon the steady-state profile. The data presented here on sinusoidal gusts are at best initial representations and should be treated as such in design studies.

2.3.8.1.2 An Undamped-Damped Sinusoidal Gust Model. The sinusoidal gust profile model presented in this section is an extension of the one presented in section 2.3.8.1.1. This model is recommended for idealized analysis to determine to what wind profile perturbations (wavelengths) and amplitudes a vehicle's guidance and control systems and structures responds. The gust model is for wind components ($u'$ and $v'$). It is completely defined by a simple undamped-damped sine function in terms of gust length, $L$ (2 times $L$ equals wavelength), and phase angle, $f$, by:

$$u' = v' = a_1\, e^{[b(H-q)H]} \sin\left[\left[\frac{p\,H}{L}\right] + f\right], \qquad (2.73)$$

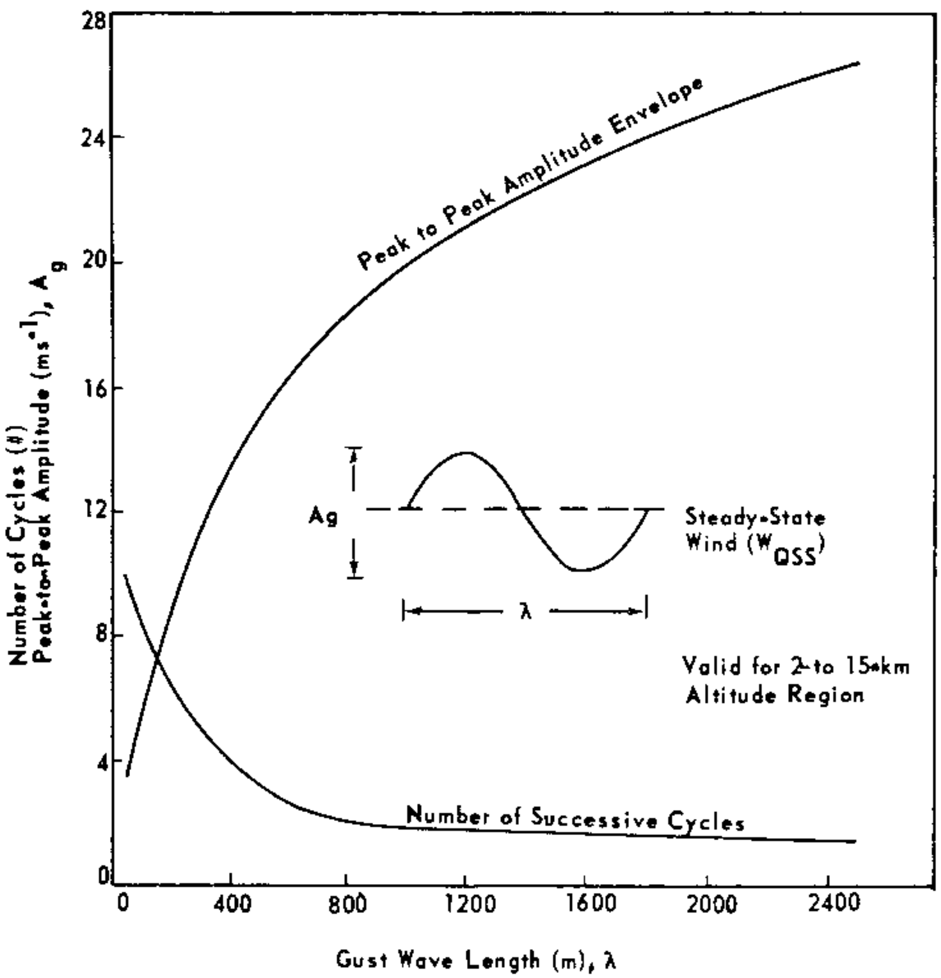



FIGURE 2-23. Best Estimate Of Expected (≥99 Percentile) Gust Amplitude and Number of Cycles as A Function Of Gust Wavelength.

where

$H$ = altitude, km

$L$ = gust length, km

$f$ = phase angle in radians, $-p/2 \leq f \leq p/2$

$u'$ and $v'$ = components, $\mathrm{ms}^{-1}$

and

$b = 0.0110\ \mathrm{km}^{-2}$ for $(0 \leq H \leq 12)$ for all $L$'s

$b = -0.0025\ \mathrm{km}^{-2}$ for $(12 < H \leq 24)$ for all $L$'s

and $a_1$ is a function of $L$ for the altitude intervals given in the following table.

Gust Length ($L$) versus Coefficient $a_1$ for Two Altitude Regimes ($H$)

| $L$ | $a_1$ ($ms^{-1}$) | |
|---|---|---|
| (m) | $0 \leq H \leq 12$ (km) | $12 < H \leq 24$ (km) |
| 400 | 2.95 | 5.6375 |
| 800 | 5.00 | 9.5600 |
| 1,600 | 7.00 | 13.3834 |

Three gust lengths are given in this model. The gust amplitude depends on the gust length. For only three phase angles between the components there are nine possible combinations for each of the three gust lengths. Figures 2-24 to 2-26 illustrate the *u*-component gust model for the three phases and the three gust lengths. It is recommended that the first engineering analysis be performed using the gust component in-phase and then out-of-phase for each of the three gust lengths added to the profiles of the monthly mean wind components as shown in figures 2-27 and 2-28 for a zero-phase angle and a gust length, $L$, of 800 m.

The gust profile model may also be applied to any other wind component percentile profile or the envelope of the profile of wind vector ellipses. The most unrealistic characteristic of this model is the number of idealized perturbations versus altitude. The amplitudes are in good agreement with the wind shear statistics for corresponding shear intervals and gust lengths. It is no more severe than that given by the previous sinusoidal gust model.

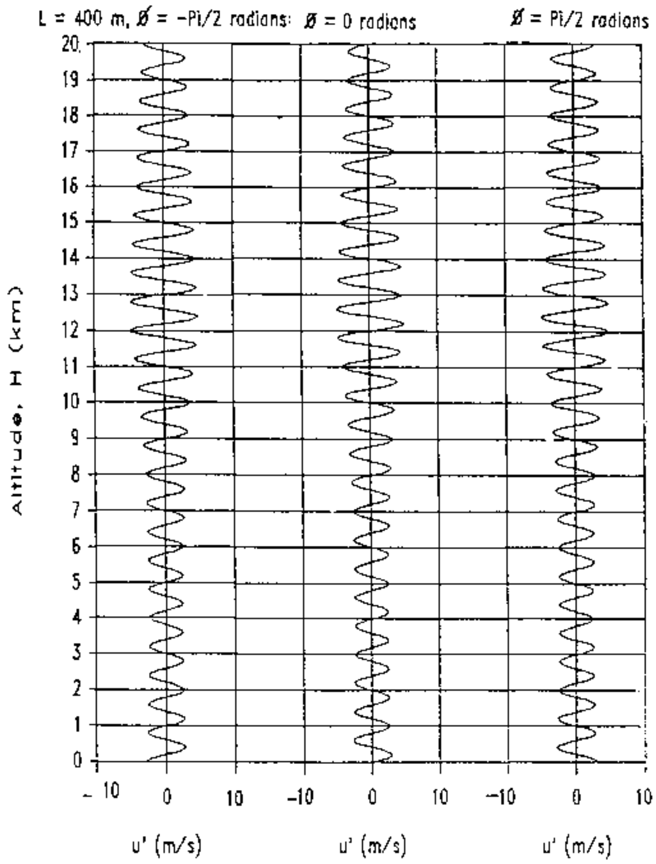



FIGURE 2-24. Undamped-Damped Sine Gust Model.

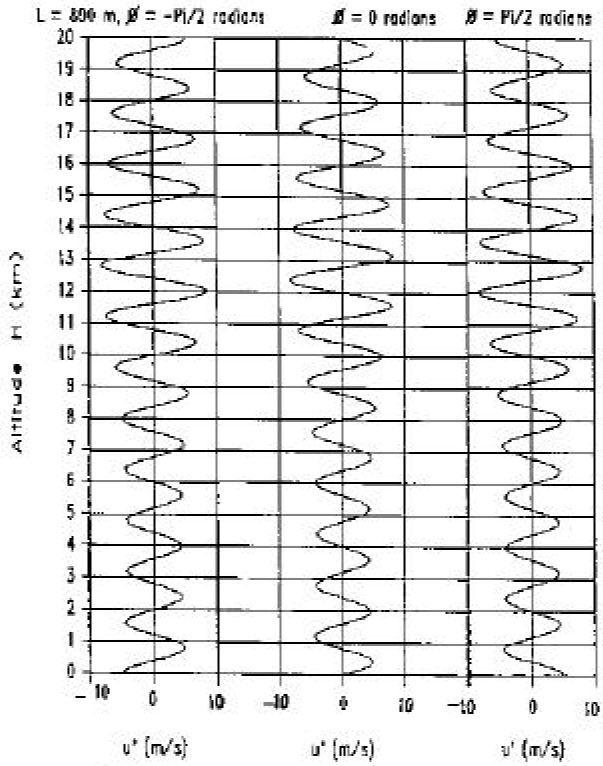



Figure 2-25. Undamped-damped sine gust model.

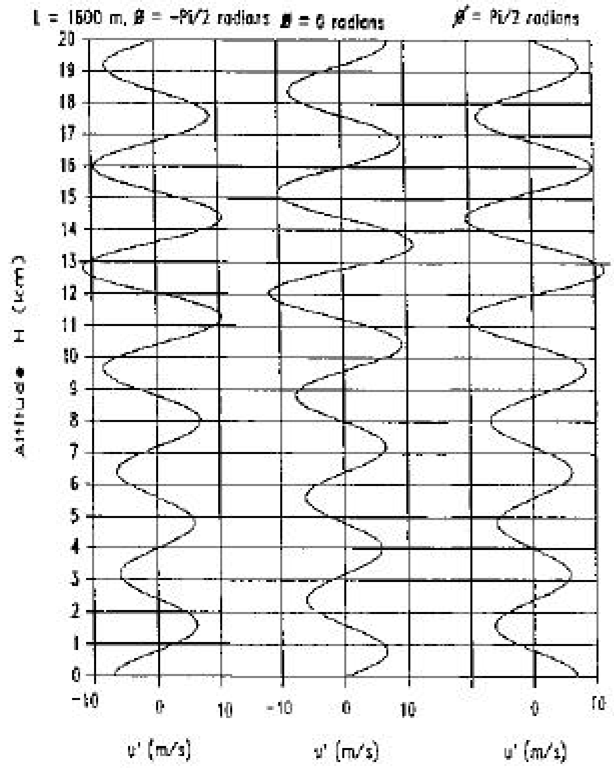



Figure 2-26. Undamped-damped sine gust model.

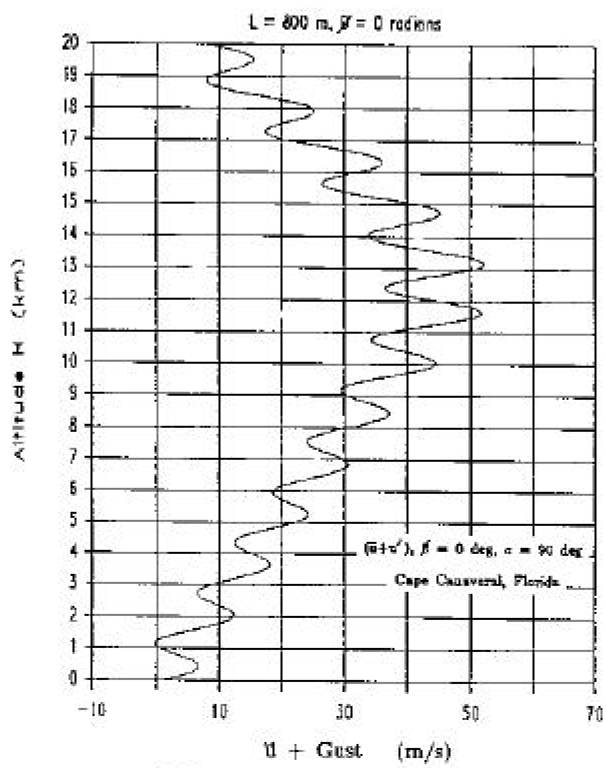



Figure 2-27. Mean zonal wind component combined with gust.

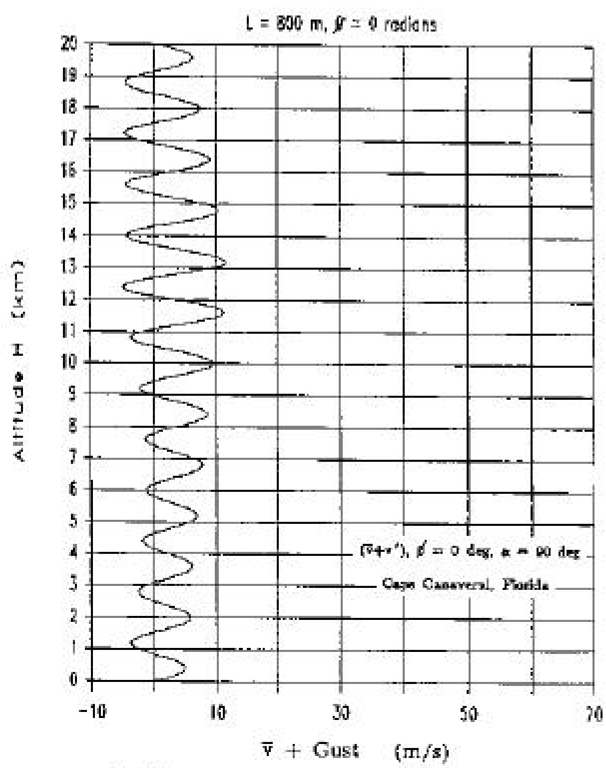



Figure 2-28. Mean meridional wind component combined with gust.

2.3.8.2 Gust Spectra. In general, the small-scale motions associated with vertical detailed profiles of wind are characterized by a superposition of discrete gusts and many random components. Spectral methods have been employed to specify the characteristics of this superposition of small-scale motions.

A digital filter was developed to separate small-scale motions from the steady-state wind profile. The steady-state wind profile defined by the separation process approximates those obtained by the rawinsonde system.* Thus, a spectrum of small-scale motions is representative of the motions included in the FPS-16 radar/jimsphere measurements, which are not included in the rawinsonde measurements. Therefore, a spectrum of those motions should be considered in addition to the steady-state wind profiles to obtain an equivalent representation of the detailed wind profile. Spectra of the small-scale motions for various probability levels have been determined and are presented in figure 2-29. The spectra were computed from approximately 1,200 detailed wind profile measurements by computing the spectra associated with each profile and then determining the probabilities of occurrence of spectral density as a function of vertical wave numbers (cycles/4,000 m). Thus, the spectra represent envelopes of spectral density for the given probability levels.

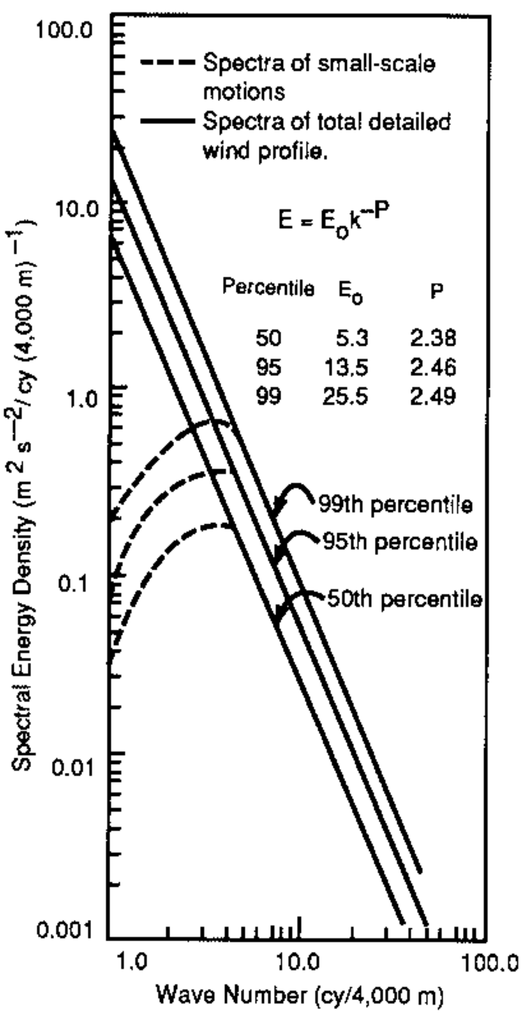



FIGURE 2-29. Spectra of Detailed Wind Profiles.

*This definition was selected to enable use of the much larger rawinsonde data sample in association with a continuous-type gust representation.

Spectra associated with each profile were computed over the altitude range between approximately 4 and 16 km. It has been shown that energy (variance) of the small-scale motions is not vertically homogeneous, that is, it is not constant with altitude. The energy content over limited altitude intervals and for limited wave number bands may be much larger than that represented by the spectra in figure 2-29. This should be kept in mind when interpreting the significance of vehicle responses when employing the spectra of small-scale motions. Additional details on this subject are available upon request. Envelopes of spectra for detailed profiles without filtering (solid lines) are also shown in figure 2-29.

These spectra are well represented for wave numbers ≥5 cycles per 4,000 m by the equation

$$E(k) = E_0 k^{-P} \ , \qquad (2.74)$$

where $E$ is the spectral density at any wave number $k$ (cycles/4,000 m) between 1 and 20, $E_0 = E(1)$, and $p$ is a constant for any particular percentile level of occurrence of the power spectrum.

Spectra of the total wind speed profiles may be useful in control systems and other slow response parametric studies for which the spectra of small-scale motions may not be adequate.

The power spectrum recommended for use in elastic body studies is given by the following expression:

$$E(k) = \frac{683.4\,(4{,}000\,k)^{1.62}}{1+0.0067\,(4{,}000\,k)^{4.05}} \ , \qquad (2.75)$$

where the spectrum $E(k)$ is defined so that integration over the domain $0 \le k \le \infty$ yields the variance of the turbulence. In this equation $E(k)$ is now the power spectral density ($m^2\ s^{-2}$/(cycles per meter)) at wave number $k$ (cycles per meter). This function represents the 99-percentile scalar wind spectra for small-scale motions given by the dashed curve and its solid line extension into the high wave number region in figure 2-29. The associated design turbulence loads are obtained by multiplying the load standard deviations by a factor greater than one to reflect an acceptable level of risk. For example, a factor of 3 will correspond to a risk of 0.99865, assuming the small scale motions constitute a Gaussian process. (Spectra for meridional and zonal components are available upon request.)

An alternate power spectrum specification has been developed (Ref. 2-59) by combining an analysis of jimsphere wind measurements and knowledge of the spectrum of clear-air turbulence (CAT) at scales smaller than those reliably measured by jimsphere. The spectrum covering wavelengths from 1,000 m to 200 m was determined by finding the spectrum that only one spectrum computed from a random sample of 100 jimsphere profiles would have a power spectral density greater than somewhere in the 1,000-m to 200-m range. The part of the spectrum with the $k^{-2.4}$ shape is the result. Then to cover wavelengths smaller than 200 m, an isotropic type spectrum corresponding to moderate CAT was added, the $k^{-5/3}$ part. The spectra are specified as:

$$E(k_z) = 5.3(10^{-4})\, k_z^{-2.4} + 1(10^{-2}) k_z^{-5/3} \ , \ \text{for } z \ge 10 \text{ km} \ ,$$

and

$$E(k_z) = 2.4(10^{-4})\, k_z^{-2.4} + 1(10^{-2}) k_z^{-5/3} \ , \ \text{for } z < 10 \text{ km} \ ,$$

where

$k_z$ = vertical wave number (cycles/meter)

$z$ = altitude above mean sea level (km).

These spectra are based on KSC measurements but are expected to be applicable at other locations since research suggests that small-scale motions are nearly universal in amplitude. However, the 99-percent spectral envelope level and moderate CAT do not apply near thunderstorms or other locations where turbulence is categorized as severe.

Vehicle responses obtained from application of these turbulence spectra should be added to rigid vehicle responses resulting from use of the synthetic wind speed and wind profile (with the 0.85 factor on shears) but without a discrete gust. One method of application is to inverse Fourier transform from wave number space to height space with random, uniformly distributed phase spectra and add the transformed small-scale winds to synthetic profiles in a Monte Carlo analysis.

2.3.9 Synthetic Wind Speed Profiles. Methods of constructing synthetic wind speed profiles are described herein. One method uses design wind speed profile envelopes (section 2.3.5) and discrete gusts or spectra (section 2.3.8) without considering the correlation between the shears and gusts. Another method (section 2.3.9.2) takes into account the relationships between the wind shear and gust characteristics.

2.3.9.1 Synthetic Wind Speed Profiles for Vertical Flight Path Considering Only Speeds and Shears. In the method that follows, correlation between the design wind speed profile envelope and wind shear envelope is considered. The method is illustrated with the 95-percentile design non directional (scalar) wind speed profile and the 99-percentile scalar wind speed buildup for KSC (fig. 2-30) and is stated as follows:

a. Start with a speed on the design wind speed profile envelope at a selected (reference) altitude.

b. Subtract the amount of the shear (wind speed change) for each required altitude layer from the value of the wind speed profile envelope at the selected altitude. Figure 2-30 presents an example of a 99-percentile shear buildup envelope starting from a reference altitude of 11 km on the KSC 95-percentile wind speed profile envelope (Table 2-49). The 10-km wind speed of 41.3 m/s is determined by subtracting 31.7 m/s (i.e., a linearly interpolated shear value for 73 m/s from the 1,000-m column of Table 2-64), from 73 m/s.

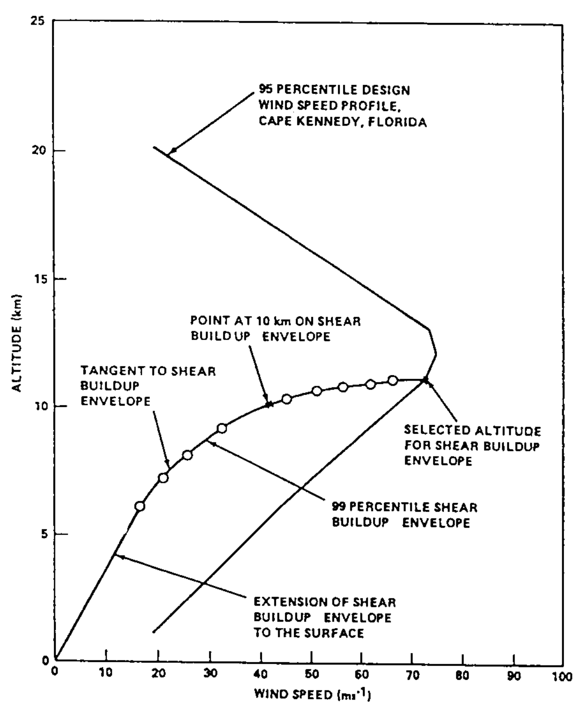


FIGURE 2-30. Example of Synthetic Wind Speed Profile Construction Without Addition of Gust.

c. Plot values obtained for each altitude layer at the corresponding altitudes. (The value of 41.3 m/s, obtained in the example in b, would be plotted at 10 km.) Continue plotting values until a 5,000-m layer is reached (5,000-m below the selected altitude).

d. Draw a smooth curve through the plotted points starting at the selected altitude on the wind speed profile envelope. The lowest point is extended from the origin with a straight line tangent to the plotted shear buildup curve. This curve then becomes the shear build-up envelope.

2.3.9.2 Synthetic Wind Speed Profiles for Vertical Flight Path Considering Relationships Between Speeds, Shears, and Gusts. In the construction of a synthetic wind speed profile, the lack of perfect correlation between the wind shear and gust can be taken into account by multiplying the shears (wind speed changes) (section 2.3.6) and the recommended design discrete gusts (section 2.3.8) by a factor of 0.85 before constructing the synthetic wind profile. This is equivalent, as an engineering approximation, to taking the combined 99-percentile values for the gusts and shears in a perfectly correlated manner. This approach was used successfully in both the Apollo/Saturn and space shuttle vehicle development programs.

Thus, to construct the synthetic wind speed profile (considering relationships between shears, speeds, and gusts, using the design wind speed envelopes given in section 2.3.5), the procedure that follows is used.

a. Construct the shear buildup envelope in the way described in section 2.3.9.1, except multiply the values of wind speed change used for each scale-of-distance by 0.85. (In the example for the selected altitude of 11 km, the point at 10 km will be found by using the wind speed change of 31.2 x 0.85, or 25.5 m/s.) This value subtracted from 73 m/s then gives a value of 46.5 m/s for the point plotted at 10 km instead of the value of 41.8 m/s used when shear and gust relationships were not considered.

b. The discrete gust is superimposed on the buildup wind shear envelope/wind speed profile envelope by adding the gust given by equation (2.69) with leading edge in the region $H_b \leq H \leq H_b + 30$ m replaced with equation (2.71). The base of the discrete gust is located at the intersection of the buildup wind shear envelope and the wind speed profile envelope (fig. 2-32). The gust amplitude, $A$, shall be multiplied by a factor of 0.85 to account for the nonperfect correlation between shears and gusts. Figure 2-32 gives an example of a synthetic profile with shears and gust in combination.

c. When the gust ends at the design wind envelope, the synthetic wind profile may follow the design wind speed envelope or shear back-off profile. If the synthetic wind profile follows the design wind speed envelope, then the trailing edge of the discrete gust will be a 1-cosine shape as given by equation (2.69). If the synthetic wind profile follows the shear back-off profile, then the trailing edge of the discrete gust will be that given by equation (2.72). This modified gust shape will guarantee a continuous transition from the gust to the back-off shear envelope. Vehicle response through both the wind profile envelope with gusts and the synthetic wind profile with shears and gusts in combination should be examined.

d. If a power spectrum representation (section 2.3.8.2) is used, then disregard all previous references to discrete gusts. Use the 0.85 factor on shears and apply the spectrum as given in section 2.3.8.2.

Figures 2-31 and 2-32 show an example using the 95-percentile design wind speed profile envelope, the 99-percentile wind speed buildup envelope, and the modified 1-cosine discrete gust shape.

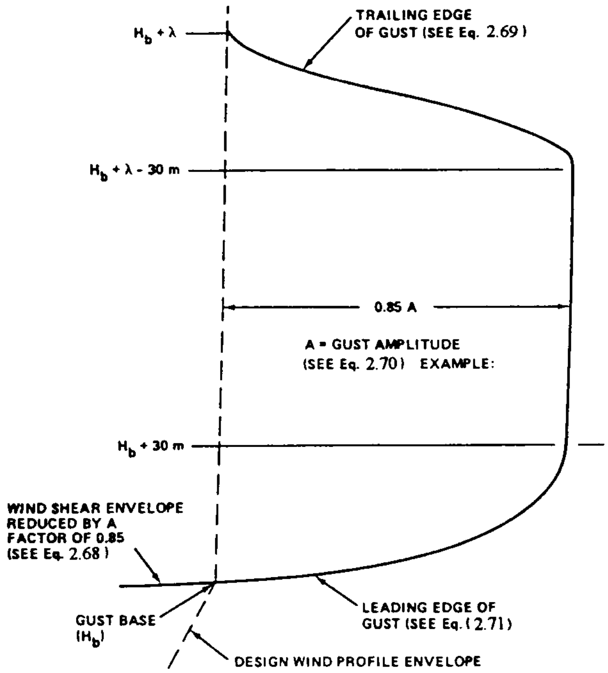



FIGURE 2-31. Relationship Between Revised Gust Shape, Design Wind Profile Envelope, and Speed Buildup (Shear) Envelope.

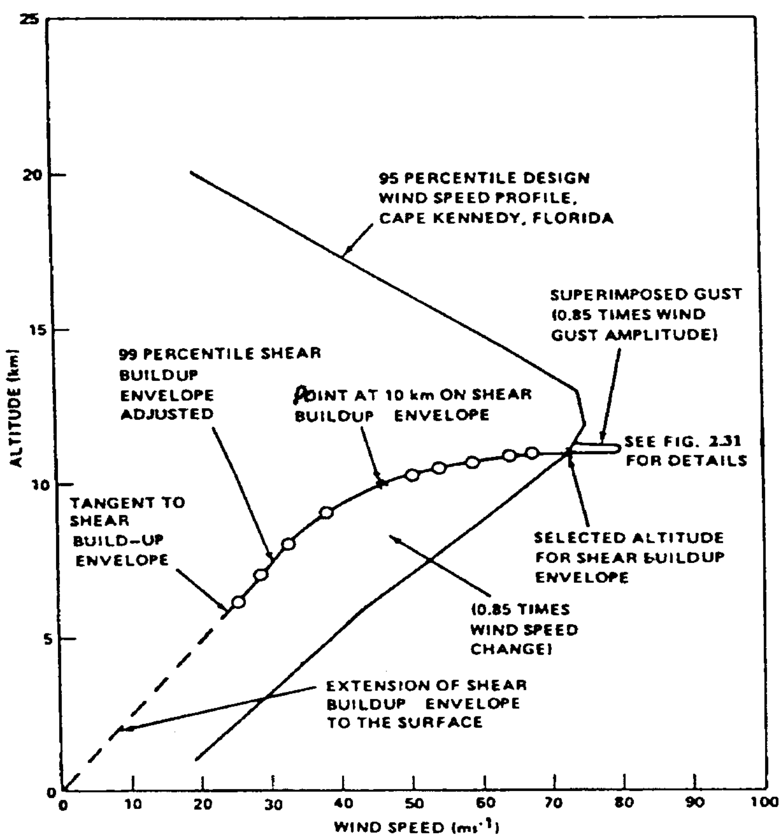


FIGURE 2-32. Example of Synthetic Wind Profile Construction, With Relationship of Wind Shears and Gusts Assumed.

2.3.9.3 Synthetic Wind Profile Merged to the Ground Wind Profile. Up to this point we have considered only those wind shear envelopes which are linearly extrapolated to a zero wind condition at the ground. This procedure does not allow for the possibility of the vehicle to enter a wind shear envelope/gust above the $H$ = 1,000-m altitude in a perturbed state resulting from excitations of the control system by the ground wind profile and the associated ground wind shears and gusts. To allow for these possibilities, it is recommended that the wind shear envelopes which begin above the 3,000-m level be combined with the wind profile envelope and discrete gust as stated in section 2.3.9.2; however, a linear extrapolation shall be used to merge the wind defined by the shear envelope at the 3,000-m level with the 1,000-m wind on the wind profile envelope.

The steady-state ground wind profile up to the 150-m level is defined by the peak wind profile (section 2.2.5.2) reduced to a steady-state wind profile by division with a 10-min average gust factor profile (section 2.2.7.1). To merge, this steady-state wind speed in the layer between 150 to 300 m shall take on a constant value equal to the steady-state wind at the 150-m level defined by the peak wind profile and gust factor profile between the surface of the Earth and the 150-m level. The flow between the 300-m level and the 1,000-m level shall be obtained by linear interpolation. If the discontinuities in slope of the wind profile at the 150-, 300-, and 1,000-m levels resulting from this merging procedure introduce significant false vehicle responses, it is recommended that this interpolation procedure be replaced with a procedure involving a smooth continuous function which closely approximates the piece-wise linear segment interpolation function between the 150- and 1,000-m levels with continuous values of wind speed and slope at the 150- and 1,000-m levels.

2.3.9.4 Synthetic Wind Speed Profiles for Nonvertical Flight Path. To apply the synthetic wind profile for other than vertical flight, multiply the wind shear buildup and back-off values by the cosine of the angle between the vertical axis (Earth-fixed coordinate system) and the vehicle's flight path. The gust (or turbulence spectra) is applied directly to the vehicle without respect to the flight path angle. The synthetic wind profile is otherwise developed according to procedures given in section 2.3.9.2.

2.3.10 Vector Wind and Vector Wind Shear Models

2.3.10.1 Vector Wind Profile Models. This subsection presents the concepts for a vector wind profile model, an outline of procedures to compute synthetic vector wind profiles (SVWP) followed by examples, and some suggestions for alternate approaches. Applications of the theoretical relationships between the variables and the parameters of the multivariate probability distribution function are made. The vector wind profile models presented in this section have potential applications for aerospace vehicle ascent and reentry analysis for the altitude range from 1 to 27 km for KSC, FL, and VAFB, CA (Ref. 2-38).

2.3.10.2 Vector Wind Profile Model Concepts.

Purpose of a Model. What is a model? One definition is that a model is a representation of one or more attributes or characteristics to make the real wind profiles more understandable and less complicated for certain engineering applications.

The modeling tools are those of mathematical probability theory and statistical analysis of wind data samples. Hopefully, through these methods, a wind model can be derived that will be a cost saving device for use in aerospace vehicle programs and still be sufficiently representative of the real wind profiles to answer engineering questions that arise in the aerospace vehicle analysis. However, the most realistic test of aerospace vehicle performance is an evaluation by flight simulations through detailed wind profiles. A sample of 150 detailed wind profiles (jimsphere wind profiles) for each month for KSC has been made available (see subsection 2.3.12.1). A sample of 150 detailed wind profiles for each month which have all the power spectra characteristics that measured jimsphere profiles have for VAFB has been made available for flight simulations for aerospace vehicle flights from VAFB. These two detailed wind profile data samples have the same moment statistical parameters at 1-km intervals (within statistical confidences) as the 14 parameters presented in the referenced report (Ref. 2-38). This was the basis for the selection of the 150 detailed wind profiles for each month.

Synthetic Vector Wind Model. In this discussion, it is assumed that the reader is familiar with the synthetic scalar wind profile model presented in this document. By definition, the synthetic scalar wind profile model is the locus of wind speeds versus altitude obtained from conditional wind shears given a specified wind speed at a reference altitude. The profile is constructed by subtracting the conditional wind shears from the specified wind speed. The scalar wind shears are a function of wind speed only. The SVWP extends this concept to the vector wind representation. For the SVWP, the vector wind shears are a function of: (a) the reference altitude; (b) the given wind vector at the reference altitude, which makes the conditional vector wind shears wind-azimuth dependent; (c) the conditional wind shears; and (d) the monthly reference period. References 2-53 and 2-54 give some engineering results using the SVWP model.

For a given wind vector, the SVWP has three dimensions, whereas the synthetic scalar wind profile has two dimensions. A wind vector is selected at the reference altitude $H_o$, and the conditional vector wind shears are computed for altitudes $H$ below and above $H_o$. The conditional wind shears are then subtracted from the given wind vector at $H_o$. For two-point separation in altitude ($H_o$–$H$), the cone formed by this procedure contains a specified percentage of the wind vectors at altitude $H$ for the given wind vector at $H_o$. The base is an ellipse in which a specified percentage (usually taken as 99 percent) of the wind vectors will lie given the wind vector at $H_o$. The interest in modeling the wind profile is to make some logical or orderly choice to arrive at the conditional wind vectors versus altitude. It is illustrated in reference 2-38 that there are an infinite number of paths along the surface of the conditional cone from reference altitude $H_o$ down to level $H$. Hence, a choice of an orderly path along the surface of the conditional cone of wind vectors should be dictated by the desired scientific or engineering application. A step-by-step procedure is given to compute the SVWP that is in-plane with the given wind vector. This in-plane profile has two branches: one is the smallest conditional vector wind and has the largest shears, and the other is the outer branch, which has the largest in-plane conditional wind vector but not necessarily the largest shear. Also presented is the SVWP derived from the tangent intercepts to the conditional vector winds. These out-of-plane synthetic vector wind profiles have two branches: a right-turning wind direction and a left-turning wind direction with respect to altitude. The two-part, in-plane SVWP and the two-part, out-of-plane SVWP give a total of four synthetic vector wind profiles.

An actual example of the conditional vector winds are shown in reference 2-38 (fig. 15). The example was derived from the December wind parameters for VAFB. The reference altitude $H_o$ is 10 km; the given wind vector at $H_o$ is from 330° at 57.8 m/s or, in terms of the components, $u^* = 28$ m/s and $v^* = -50$ m/s. Instead of conditional ellipses, 99-percent conditional circles have been computed for each altitude at 1-km intervals from 0- to 27-km altitude. As presented, the dashed line connecting the center of the conditional circles versus altitude is the conditional mean vector. The smooth curve connecting the intercepts of the conditional circles is the in-plane SVWP that has the largest conditional shears.

2.3.10.3 Computation of the Synthetic Vector Wind Profile. Discussion in reference 2-38 is sufficiently detailed for a computer program development to code the procedures to compute the SVWP. Digressions are made in the procedures to clarify some points. The primary objectives, however, are to illustrate some applications of the probability theory of vector winds and to show the use of the tabulated wind statistical parameters to compute synthetic vector wind profiles.

2.3.10.4 Monthly Enveloping Wind Probability Ellipse (MEWPE). The five adjusted parameters, given in Table 2-74 for KSC and Table 2-75 for VAFB, are used to obtain the 99-percent probability ellipse at each altitude that envelops the monthly 99-percent ellipses. This procedure is more desirable than using the annual bivariate normal statistical parameters because the annual parameters are from a

Table 2-74. KSC Adjusted Bivariate Normal Statistics*

| Alt.(km) | UA(m/s) | SAU(m/s) | R(U,V) | VA(m/s) | SAV(m/s) |
|---|---|---|---|---|---|
| 0 | –0.296 | 3.587 | –0.120 | –0.168 | 3.691 |
| 1 | 2.482 | 7.568 | 0.084 | 1.620 | 6.793 |
| 2 | 6.107 | 8.325 | 0.115 | 1.484 | 6.821 |
| 3 | 9.184 | 9.025 | 0.118 | 1.684 | 7.399 |
| 4 | 12.432 | 10.025 | 0.132 | 2.105 | 8.095 |
| 5 | 15.807 | 11.200 | 0.165 | 2.487 | 8.978 |
| 6 | 19.229 | 12.357 | 0.203 | 2.979 | 9.612 |
| 7 | 22.465 | 13.785 | 0.232 | 3.369 | 10.498 |
| 8 | 25.653 | 15.299 | 0.250 | 3.397 | 11.538 |
| 9 | 29.370 | 16.976 | 0.260 | 3.389 | 12.666 |
| 10 | 31.872 | 18.523 | 0.265 | 2.462 | 14.187 |
| 11 | 32.983 | 20.080 | 0.261 | 1.266 | 15.577 |
| 12 | 31.529 | 20.909 | 0.278 | –0.766 | 15.955 |
| 13 | 28.098 | 20.540 | 0.309 | –1.494 | 14.967 |
| 14 | 25.102 | 18.523 | 0.339 | –1.833 | 12.772 |
| 15 | 23.029 | 15.954 | 0.344 | 0.010 | 10.811 |
| 16 | 21.111 | 13.717 | 0.323 | 0.329 | 9.391 |
| 17 | 17.574 | 11.766 | 0.291 | 0.705 | 7.957 |
| 18 | 13.431 | 10.248 | 0.268 | 0.794 | 6.303 |
| 19 | 8.172 | 9.354 | 0.253 | 0.583 | 4.901 |
| 20 | 3.374 | 8.869 | 0.214 | –0.141 | 4.141 |
| 21 | 0.941 | 8.740 | 0.141 | 0.179 | 4.230 |
| 22 | 0.651 | 8.974 | 0.097 | –0.140 | 4.103 |
| 23 | 0.562 | 9.363 | 0.097 | –0.023 | 4.098 |
| 24 | 1.611 | 10.273 | 0.109 | 0.329 | 3.969 |
| 25 | 2.835 | 11.219 | 0.137 | 0.486 | 4.256 |
| 26 | 3.830 | 12.266 | 0.156 | 0.661 | 4.632 |
| 27 | 5.083 | 13.040 | 0.172 | 1.109 | 5.315 |
| 28 | 6.866 | 13.407 | 0.261 | 2.210 | 5.130 |
| 29 | 8.141 | 14.685 | 0.296 | 2.384 | 5.564 |
| 30 | 11.355 | 15.594 | 0.321 | 3.360 | 5.950 |
| 32 | 9.482 | 16.544 | 0.256 | 5.610 | 7.629 |
| 34 | 14.036 | 18.595 | 0.224 | 4.604 | 8.649 |
| 36 | 16.852 | 20.164 | 0.126 | 1.602 | 8.601 |
| 38 | 16.271 | 21.514 | 0.150 | 4.108 | 9.798 |
| 40 | 15.123 | 22.758 | 0.244 | 7.786 | 10.470 |
| 42 | 14.753 | 24.487 | 0.334 | 8.480 | 11.850 |
| 44 | 16.079 | 26.769 | 0.358 | 8.950 | 12.340 |
| 46 | 14.703 | 28.956 | 0.255 | 10.840 | 13.710 |
| 48 | 15.617 | 30.658 | 0.243 | 10.065 | 13.223 |
| 50 | 14.219 | 31.726 | 0.217 | 9.170 | 13.932 |
| 52 | 16.943 | 32.413 | 0.169 | 9.223 | 15.504 |
| 54 | 17.726 | 33.891 | 0.185 | 9.810 | 14.900 |
| 56 | 15.871 | 34.430 | 0.237 | 11.900 | 15.700 |
| 58 | 14.117 | 35.760 | 0.271 | 11.366 | 15.594 |
| 60 | 14.518 | 36.407 | 0.298 | 13.270 | 16.570 |
| 62 | 4.837 | 41.488 | 0.266 | 6.471 | 17.965 |
| 64 | 5.219 | 45.358 | 0.197 | 6.311 | 18.154 |
| 66 | 17.022 | 46.408 | 0.100 | 1.558 | 20.768 |

Table 2-75. VAFB Adjusted Bivariate Normal Statistics*

| Alt.(km) | UA(m/s) | SAU(m/s) | R(U,V) | VA(m/s) | SAV(m/s) |
|---|---|---|---|---|---|
| 0 | 1.192 | 3.103 | –0.582 | –1.486 | 3.653 |
| 1 | 0.750 | 4.320 | –0.157 | –1.577 | 7.412 |
| 2 | 3.070 | 5.640 | –0.159 | –2.172 | 8.476 |
| 3 | 5.790 | 7.290 | –0.122 | –2.852 | 9.606 |
| 4 | 8.280 | 9.080 | –0.083 | –4.385 | 11.172 |
| 5 | 10.385 | 10.561 | –0.021 | –4.570 | 12.420 |
| 6 | 12.214 | 12.058 | 0.030 | –4.860 | 14.100 |
| 7 | 14.317 | 13.481 | 0.076 | –5.320 | 15.810 |
| 8 | 16.031 | 15.029 | 0.110 | –5.550 | 17.130 |
| 9 | 17.520 | 16.180 | 0.157 | –5.307 | 18.149 |
| 10 | 19.660 | 17.210 | 0.174 | –5.299 | 18.934 |
| 11 | 21.600 | 17.300 | 0.170 | –4.504 | 18.486 |
| 12 | 23.082 | 16.336 | 0.154 | –3.472 | 17.415 |
| 13 | 21.535 | 14.229 | 0.128 | –2.698 | 15.190 |
| 14 | 19.891 | 12.588 | 0.098 | –2.160 | 13.162 |
| 15 | 16.982 | 10.876 | 0.047 | –2.243 | 10.786 |
| 16 | 14.570 | 9.355 | 0.008 | –2.349 | 9.099 |
| 17 | 11.340 | 7.968 | –0.019 | –2.395 | 7.608 |
| 18 | 8.467 | 7.247 | –0.039 | –1.880 | 6.198 |
| 19 | 5.527 | 6.491 | –0.053 | –1.939 | 5.111 |
| 20 | 4.021 | 6.184 | –0.065 | –1.835 | 4.225 |
| 21 | 2.340 | 6.480 | –0.094 | –2.422 | 3.790 |
| 22 | 0.730 | 7.100 | –0.066 | –2.660 | 3.790 |
| 23 | –0.170 | 7.700 | –0.016 | –2.633 | 3.694 |
| 24 | –0.830 | 8.970 | 0.027 | –2.860 | 3.940 |
| 25 | –1.060 | 10.350 | 0.069 | –2.590 | 4.130 |
| 26 | –0.840 | 11.790 | 0.121 | –2.424 | 4.548 |
| 27 | –0.330 | 13.280 | 0.163 | –2.530 | 5.080 |
| 28 | 1.285 | 14.752 | 0.205 | –2.700 | 5.940 |
| 29 | 2.537 | 16.515 | 0.228 | –2.690 | 6.740 |
| 30 | 4.141 | 18.307 | 0.248 | –2.480 | 7.580 |
| 32 | 12.870 | 21.230 | 0.205 | –1.174 | 7.804 |
| 34 | 20.660 | 24.500 | 0.286 | –0.756 | 8.907 |
| 36 | 24.996 | 26.947 | 0.344 | –0.130 | 9.800 |
| 38 | 28.187 | 29.450 | 0.310 | 0.070 | 10.530 |
| 40 | 31.206 | 30.569 | 0.259 | –0.564 | 11.581 |
| 42 | 36.167 | 31.664 | 0.255 | 1.905 | 13.792 |
| 44 | 40.478 | 33.152 | 0.243 | 2.916 | 15.365 |
| 46 | 42.923 | 35.135 | 0.252 | 6.740 | 18.450 |
| 48 | 44.999 | 36.966 | 0.285 | 8.720 | 19.030 |
| 50 | 45.371 | 39.033 | 0.276 | 11.150 | 19.204 |
| 52 | 45.250 | 40.967 | 0.279 | 14.396 | 18.804 |
| 54 | 45.666 | 42.131 | 0.286 | 14.040 | 18.922 |
| 56 | 41.941 | 43.665 | 0.264 | 12.030 | 18.450 |
| 58 | 37.535 | 45.109 | 0.286 | 11.210 | 21.120 |
| 60 | 33.377 | 47.988 | 0.256 | 8.850 | 24.060 |
| 62 | 22.936 | 48.100 | 0.186 | 3.570 | 28.780 |
| 64 | 27.992 | 49.300 | 0.153 | 7.421 | 23.010 |
| 66 | 31.660 | 49.006 | 0.045 | –2.518 | 26.311 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 68 | 19.604 | 45.477 | –0.028 | 7.418 | 23.605 | | 68 | 32.805 | 45.888 | –0.008 | 4.050 | 25.520 |
| 70 | 31.883 | 46.583 | –0.075 | 2.556 | 26.806 | | 70 | 29.956 | 46.262 | –0.070 | 2.260 | 26.056 |

*Adjusted bivariate normal statistics for ellipse at each altitude that envelops the monthly ellipses for P = 0.99. The monthly KSC statistical parameters for 0- to 27-km altitude are from the 19-year (1956 to 1974) twice daily, serially complete KSC rawinsonde data base, and for 28- to 70-km altitude they are from the KSC Range Reference Atmosphere (RCC/RRA DOC 361-83) (Ref. 2-23). VAFB 0- to 70-km altitude parameters are from VAFB RCC/RRA DOC 362-83 (Ref. 2-23).

mixture of the monthly bivariate normal distributions, and this does not insure that all monthly reference periods will contain the assigned percentage of wind vectors. The 99-percent probability ellipses at discrete altitudes are required to assure that 95-percent of the wind vector profiles will lie within the 99-percent ellipses at discrete altitudes. An application for the 99-percent MEWPE may be for range safety.

An example wind vector profile model based on MEWPE for KSC follows. The theoretical basis for the model is that the wind components of a vector at a reference altitude, $H_0$, and the wind components at any other altitude, $H$, above or below $H_0$ have a probability distribution that is quadravariate normal, where $H$ and $H_0$ range from 0 to 27 km. The wind components of the model profiles are derived from the conditional bivariate normal distribution of wind components at $H$, given the components of a wind vector at $H_0$. The given wind vectors at each reference altitude, $H_0$, are the wind vectors to the 99-percent MEWPE for clocking angles at 30º increments (0 to 330º) as measured counterclockwise from the centroid of MEWPE. The 14 quadravariate normal parameters, which include the inter- and intra-level correlation coefficients, are used to compute the 99-percent bivariate normal conditional ellipses at each altitude, $H$. The wind vector to the 99-percent conditional wind ellipse, as measured from the centroid of the conditional ellipse that is 180º from the given clocking angle at $H_0$, is selected. These wind vectors versus altitude $H$ form the wind vector profile model. For this model there are 12 wind profiles (one each for the clocking angles) for each reference altitude $H_0 = 0,1,2,...,27$ km. Hence, there are 336 wind model profiles. These profiles will be made available on electronic data transfer (only) upon request to NASA/ MSFC Earth Science and Applications Division. (This wind model has not been established for VAFB.)

The advantages of the MEWPE model are:

1. It is more realistic than the synthetic scalar wind profile model.

2. It is less complicated than the monthly synthetic vector wind profile used for STS design.

3. The mathematical formulation permits generalizations.

4. The wind vectors can be computed for any conditional probability ellipse.

5. A single model envelops all months.

This wind vector profile model has been used in ascent design studies for the National Launch System (NLS).

2.3.11 Characteristic Wind Profiles to a Height of 18 km. A significant problem in aerospace vehicle design is to provide assurance of an adequate design for flight through wind profiles of various configurations. During the major design phase of an aerospace vehicle, the descriptions of various characteristics of the wind profile are employed in determining the applicable vehicle response requirement. Since much of the vehicle is in a preliminary status of design and the desired detail data on structural dynamic modes and other characteristics are not known at this time, the use of statistical and synthetic representations of the wind profile is desirable. However, after the vehicle design has been finalized and tests have been conducted to establish certain dynamic capabilities and parameters, it is desirable to evaluate the total system by simulated dynamic flight through wind profiles containing adequate frequency resolution (Ref. 2-40). The profiles shown in figures 2-33 through 2-38 are profiles of a scalar wind measured by the FPS-16 radar/jimsphere wind measuring system, and they illustrate the following: (1) jet stream winds, (2) sinusoidal variation in wind with height, (3) high winds over a broad altitude band, (4) light wind speeds, and (5) discrete gusts.

These profiles show only a few of the possible wind profiles that can occur. Jet stream winds (fig. 2-33) are quite common over the various test ranges during the winter months and can reach magnitudes in excess of 100 m/s. These winds occur over a limited altitude range, making the wind shears very large.

Figure 2-34 depicts winds having sinusoidal behavior in the 10- to 14-km region. These types of winds can create excessive loads upon a vertically rising vehicle, particularly if the reduced forcing frequencies couple with the vehicle control frequencies and result in additive leads. Periodic variations in the vertical wind profile are not uncommon. Some variations are of more concern than others, depending upon wavelength and, of course, amplitude.

Figure 2-35 is an interesting example of high wind speeds that occurred over 6 km in depth. Such flow is not uncommon for the winter months. Figure 2-36 shows scalar winds of very low values. These winds were generally associated with easterly flow over the entire altitude interval (surface to 16 km) at KSC, FL. The last examples (figs. 2-37 and 2-38) illustrate two samples of discrete gusts.

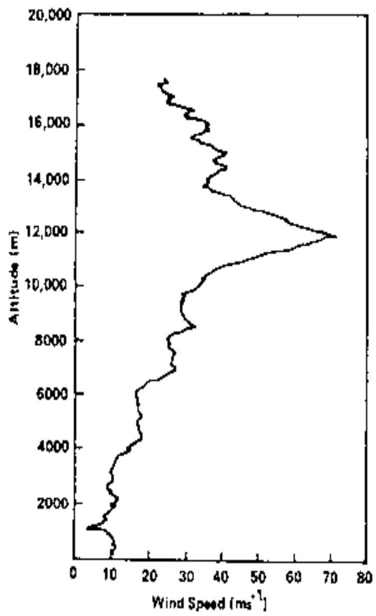



Figure 2-33. Example of jet stream winds.

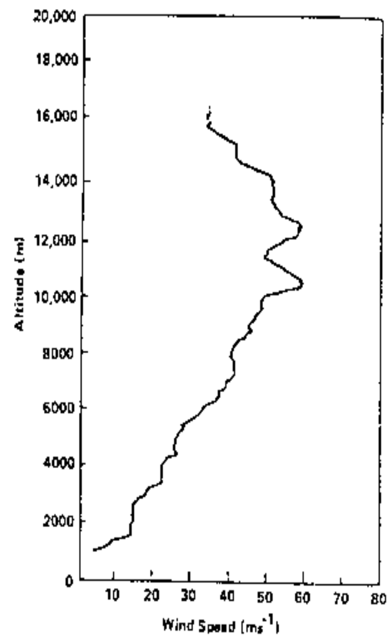



Figure 2-34. Example of sine wave flow in the 10- to 14-km altitude region.

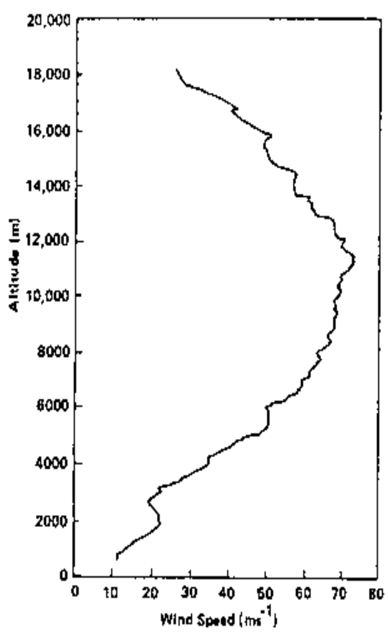



Figure 2-35. Example of high wind speeds over a deep altitude layer.

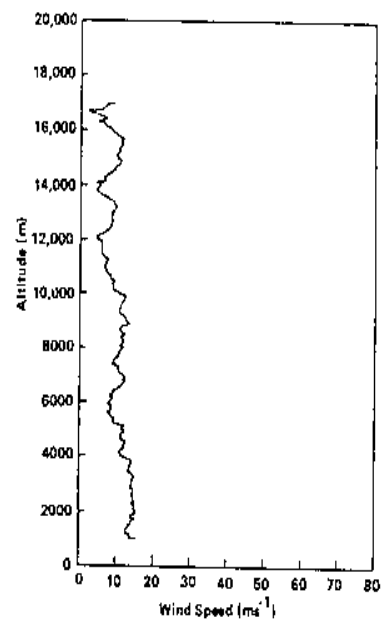



Figure 2-36. Example of low wind speeds.

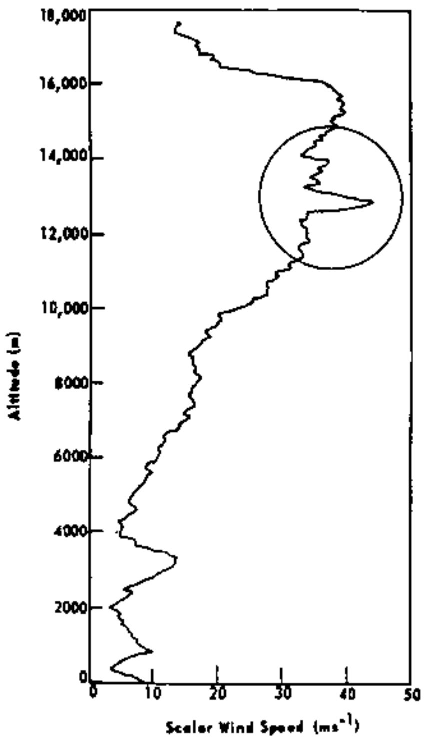



FIGURE 2-37. Example Of A Discrete Gust Observed at 1300Z on January 21, 1968, at KSC

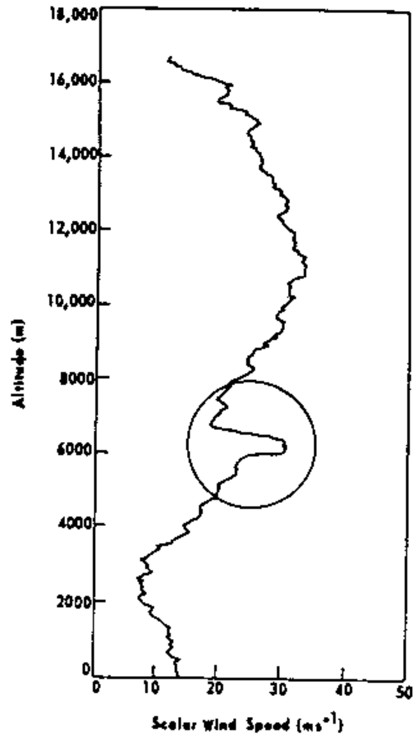



FIGURE 2-38. Example Of A Discrete Gust Observed By A Jimsphere Released at 2103Z on November 8, 1967 at KSC.

2.3.12 Wind Profile Data Availability.

2.3.12.1 KSC, FL, and VAFB, CA, Jimsphere Wind Design Assessment and Verification Data Base. The jimsphere wind design assessment and verification data tapes serve as a very special data set for wind aloft vehicle response and other analytical studies. When properly integrated into a flight-simulation program (space shuttle, for example), vehicle operational risks can be more accurately assessed relative to the true representation of wind velocity profile characteristics. The wind velocity profiles contain wind vectors for each 25 m in altitude from near surface to an altitude of approximately 18 km. The high frequency resolution is one cycle per 100 m with an rms error of approximately 0.5 m/s for velocities averaged over a 50-m height interval. Launch probability statements may be specified from flight simulations and related analyses. Through in-depth mathematical and statistical interpretations of these data, specific criteria can be generated on details of vector winds, gusts, shears, and the wind flow field interrelationships.

Two special jimsphere wind profile data sets of 150 profiles per month are available for KSC, FL, and VAFB, CA. In addition, a set of jimsphere wind profiles for 2, 3.5-, 7-, and 10.5-h pairs grouped according to summer, winter, and transition seasonal months has been prepared for KSC. A similar set of 3.5-h wind profile pairs has also been assembled for VAFB. These data sets were selected based on an extensive statistical and physical analysis of the vector wind profile characteristics and their representativeness. They have been specified for use in the space shuttle program for system design assessment, performance analysis, and prelaunch wind-loads calculations.

These data sets are available upon request to the Environments Group, ED44, NASA/George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812. There are also a large number of jimsphere wind velocity profile data available for KSC, Point Mugu, White Sands Missile Range, Green River, Wallops Island, and VAFB.

2.3.12.2 Availability of Rawinsonde Wind Velocity Profiles. A very unique serially complete, edited, and corrected rawinsonde wind profile data at 1-km intervals to approximately 30 km are available for 19 years (two observations per day) for KSC, for 9 years (four observations per day) for Santa Monica, and for 14 years (two observations per day) for VAFB. A representative serial complete rawinsonde wind profile data set is available for the Wallops Flight Center (12 years, two observations per day). Qualified requesters may obtain these data upon request to the NASA/George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812. They are also available as card deck 600 from the National Climatic Data Center, Asheville, North Carolina 28801.

2.3.12.3 Availability of Rocketsonde Wind Velocity Profiles. Rocketsonde wind profile data at 1-km intervals from approximately 20 to 75 km have been collected from various launch sites around the world. These data can be obtained from the World Data Center A, Asheville, North Carolina 28801.

2.3.12.4 Utility of Data. All wind profile data records should be checked carefully by the user before employing them in any vehicle response calculations. Wherever practical, the user should become familiar with the representativeness of the data and frequency content of the profile used, as well as the measuring system and reduction schemes employed in handling the data. For those organizations that have aerospace meteorology oriented groups or individuals on their staffs, consultations should be held with them. Otherwise, various government groups concerned with aerospace vehicle design and operation can be of assistance. Such action by the user can prevent expensive misuse and error in interpretation of the data relative to the intended application.

2.3.13 Atmospheric Turbulence Criteria for Horizontally Flying Vehicles. This section presents the continuous random turbulence model for the design of aerospace vehicles capable of flying horizontally, or nearly so, through the atmosphere. In general, both the continuous random model (sections 2.3.13 and 2.3.14) and the discrete model (section 2.3.15) are used to calculate vehicle responses, with the procedure producing the larger response being used for design.

The lateral and vertical components of turbulence are perpendicular to the relative mean wind vector and act in the lateral and vertical directions relative to the vehicle flight path. To a reasonable degree of approximation, in-flight atmospheric turbulence experienced by horizontally flying vehicles can be assumed to be homogeneous, stationary, Gaussian, and isotropic. Under some conditions, these assumptions might appear to be drastic, but for engineering purposes they seem to be appropriate, except for low-level flight in approximately the first 300 m of the atmosphere. It has been found that the spectrum of turbulence first suggested by von Karman appears to be a good analytical representation of atmospheric turbulence. The longitudinal spectrum is given by

$$F_u(W,L) = s^2 \frac{2L}{p} \frac{1}{\left[1+(1.339LW)^2\right]^{\frac{5}{6}}} , \qquad (2.76)$$

where $s^2$ is the variance of the turbulence, $L$ is the scale of turbulence, and $W$ is the wave number in units of radians per unit length. The spectrum is defined so that

$$s^2 = \int_0^\infty F_u(W,L)\, dW \; . \tag{2.77}$$

The theory of isotropic turbulence predicts that the spectra $F_w$ of the lateral components of turbulence are related to the longitudinal spectrum through the differential equation

$$F_w = \frac{1}{2}\left(F_u - W\,\frac{dF_u}{dW}\right) . \qquad (2.78)$$

Substitution of equation (2.76) into equation (2.78) yields

$$F_w = s^2 \frac{L}{p} \frac{1 + \frac{8}{3}(1.339\,LW)^2}{\left[1 + (1.339\,LW)^2\right]^{\frac{11}{6}}} . \qquad (2.79)$$

The nondimensional spectra $2pF_u/s^2L$ are depicted in figure 2-39 as functions of $WL$. As $LW > \infty$, $F_u$ and $F_w$ asymptotically behave like

$$F_u \sim s^2 \frac{2L}{p} \frac{(LW)^{-\frac{5}{3}}}{(1.339)^{\frac{5}{3}}} (LW \rightarrow \infty) \quad , \qquad (2.80)$$

$$F_w \sim s^2 \frac{8L}{3p} \frac{(LW)^{-\frac{5}{3}}}{(1.339)^{\frac{5}{3}}} (LW \rightarrow \infty) \quad , \qquad (2.81)$$

consistent with the concept of the Kolmogorov inertial subrange. In addition, $F_w/F_u \rightarrow 4/3$ as $WL \rightarrow \infty$. Design values of the scale of turbulence $L$ are given in Table 2-76. Experience indicates that the scale of turbulence increases as height increases in the first 762 m (2,500 ft) of the atmosphere, and typical values of $L$ range from 10 m (~30 ft) near the surface to 610 m (2,000 ft) at approximately a 762-m (2,500-ft) level, typical values of $L$ are in the order of 762 to 1,829 m (2,500 to 6,000 ft). The scales of turbulence in Table 2-76 above the 300-m level are probably low, and they would be expected to give a somewhat conservative or high number of load or stress exceedances per unit length of flight. The scale of turbulence indicated for the first 304.8 m of the atmosphere in Table 2-76 is a typical value. The use of this average scale of turbulence may be appropriate for load studies; however, it is inappropriate for control system and flight simulation purposes, in which event the vertical variation of the first 304.8 m of the atmosphere in Table 2-76 is a typical value. The use of this average scale of turbulence may be appropriate for load studies; however, it is inappropriate for control system and flight simulation purposes, in which event the vertical variation of the scale of turbulence in the first 300 m of the atmosphere should be taken into account.

The power spectrum analysis approach is applicable only to stationary Gaussian continuous turbulence, but atmospheric turbulence is neither statistically stationary nor Gaussian over long distances. The statistical quantities used to describe turbulence vary with altitude, wind direction, terrain roughness, atmospheric stability, and a host of other variables. Nevertheless, it is valid to a sufficient degree of engineering approximation to recommend that atmospheric turbulence be considered locally Gaussian and stationary and that the total flight history of a horizontally flying vehicle be considered to be composed of an ensemble of exposures to turbulence of various intensities, all using the same power spectrum shape. Furthermore, it is recommended that the following statistical distribution of rms gust intensities be used:

$$p(s) = \frac{P_1}{b_1}\sqrt{\frac{2}{p}}\exp\left(-\frac{s^2}{2b_1^2}\right) + \frac{P_2}{b_2}\sqrt{\frac{2}{p}}\exp\left(-\frac{s^2}{2b_2^2}\right) , \qquad (2.82)$$

where $b_1$ and $b_2$ are the standard deviations of $s$ in nonstorm turbulence. The quantities $P_1$ and $P_2$ denote the fractions of flight time or distance flown in nonstorm and storm turbulence. It should be noted that if $P_o$ is the fraction of flight time or distance in smooth air, then

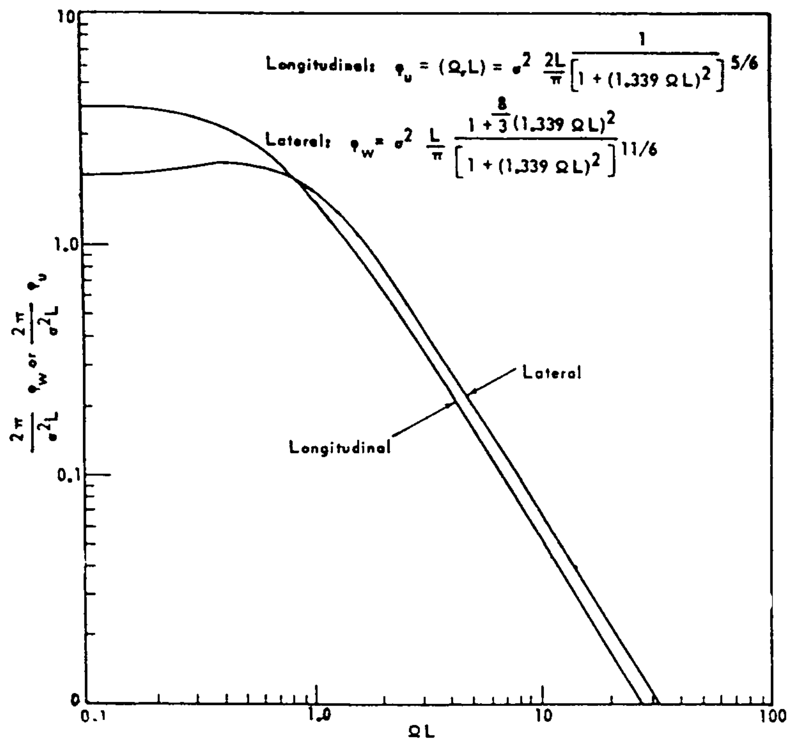



FIGURE 2-39. The Nondimensional Longitudinal and Lateral, $2pF_u/s^2L$ and $2pF_w/s^2L$, Spectra as Functions of The Dimensionless Frequency $LW$.

Table 2-76. Parameters for the Turbulence Model for Horizontally Flying Vehicles.

| Altitude | | Mission Segment* | Turbulence Component ** | $P_1$ | $b_1$ | | $P_2$ | $b_2$ | | $L$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (m) | (ft) | | | (unitless) | (m/s) | (ft/s) | (unitless) | (m/s) | (ft/s) | (m) | (ft) |
| 0–304.8 | 0–1,000 | Low Level Contour (rough terrain) | V | 1.00 | 0.82 | 2.7 | $10^{-5}$ | 3.25 | 10.65 | 152.4 | 500 |
| 0–304.8 | 0–1,000 | Low Level Contour (rough terrain) | L, L | 1.00 | 0.94 | 3.1 | $10^{-5}$ | 4.29 | 14.06 | 152.4 | 500 |
| 0–304.8 | 0–1,000 | C, C, D | V, L, L | 1.00 | 0.77 | 2.51 | 0.005 | 1.54 | 5.04 | 152.4 | 500 |
| 304.8–672 | 1,000–2,500 | C, C, D | V, L, L | 0.42 | 0.92 | 3.02 | 0.0033 | 1.81 | 5.94 | 533.4 | 1,750 |
| 672–1,524 | 2,500–5,000 | C, C, D | V, L, L | 0.30 | 1.04 | 3.42 | 0.0020 | 2.49 | 8.17 | 762 | 2,500 |
| 1,524–3,048 | 5,000–10,000 | C, C, D | V, L, L | 0.15 | 1.09 | 3.59 | 0.00095 | 2.81 | 9.22 | 762 | 2,500 |
| 3,048–6,096 | 10,000–20,000 | C, C, D | V, L, L | 0.062 | 1.00 | 3.27 | 0.00028 | 3.21 | 10.52 | 762 | 2,500 |
| 6,096–9,144 | 20,000–30,000 | C, C, D | V, L, L | 0.025 | 0.96 | 3.15 | 0.00011 | 3.62 | 11.88 | 762 | 2,500 |
| 9,144–12,192 | 30,000–40,000 | C, C, D | V, L, L | 0.011 | 0.89 | 2.93 | 0.000095 | 3.00 | 9.84 | 762 | 2,500 |
| 12,192–15,240 | 40,000–50,000 | C, C, D | V, L, L | 0.0046 | 1.00 | 3.28 | 0.000115 | 2.69 | 8.81 | 762 | 2,500 |
| 15,240–18,288 | 50,000–60,000 | C, C, D | V, L, L | 0.0020 | 1.16 | 3.82 | 0.000078 | 2.15 | 7.04 | 762 | 2,500 |
| 18,288–21,336 | 60,000–70,000 | C, C, D | V, L, L | 0.00088 | 0.89 | 2.93 | 0.000057 | 1.32 | 4.33 | 762 | 2,500 |
| 21,336–24,384 | 70,000–80,000 | C, C, D | V, L, L | 0.00038 | 0.85 | 2.80 | 0.000044 | 0.55 | 1.80 | 762 | 2,500 |
| above 24,384 | above 80,000 | C, C, D | V, L, L | 0.00025 | 0.76 | 2.50 | 0 | 0 | 0 | 762 | 2,500 |

*Climb, cruise, and descent (C, C, D).

**Vertical, Lateral, and longitudinal (V, L, L).

$$P_0+P_1+P_2=1\ . \tag{2.83}$$

The recommended design values of $P_1$, $P_2$, $b_1$, and $b_2$ are given in Table 2-76. Note that over rough terrain $b_2$ can be extremely large in the first 304 m (1,000 ft) above the terrain and the $b$'s for the vertical, the lateral, and the longitudinal standard deviations of the turbulence are not equal. Thus, in the first 304 m (1,000 ft) of the atmosphere above rough terrain, turbulence is significantly anisotropic, and this anisotropy must be taken into account in engineering calculations.

An exceedance model of gust loads and stresses can be developed with the preceding information. Let $y$ denote any load quantity that is a dependent variable in a linear system of response equations (for example, bending moment at a particular wind station). This system is forced by the longitudinal, lateral, and vertical components of turbulence and, upon producing the Fourier transform of the system, it is possible to obtain the spectrum of $y$. This spectrum will be proportional to the input turbulence spectra, the function of proportionality being the system transfer function. Upon integrating the spectrum of $y$ over the domain $0 < W < \infty$, we obtain the relationship

$$s_y = As\ , \tag{2.84}$$

where $A$ is a positive constant that depends upon the system parameters and the scale of turbulence, and $s_y$ is the standard deviation of $y$.

If the output $y$ is considered to be Gaussian for a particular value of $s$, then the expected number of fluctuations of $y$ that exceed $y^*$ with positive slope per unit distance with reference to a zero mean is

$$N(y^*) = N_0 \exp\left(\frac{y^{*2}}{2s_y^2}\right)\ , \tag{2.85}$$

where $N_0$ is the expected number of zero crossings of $y$ units distance with $h$ positive slope and is given by

$$N_0 = \frac{1}{2ps_y}\left[\int_0^\infty W^2 F_y(W)\, dW\right]^{\frac{1}{2}}\ . \tag{2.86}$$

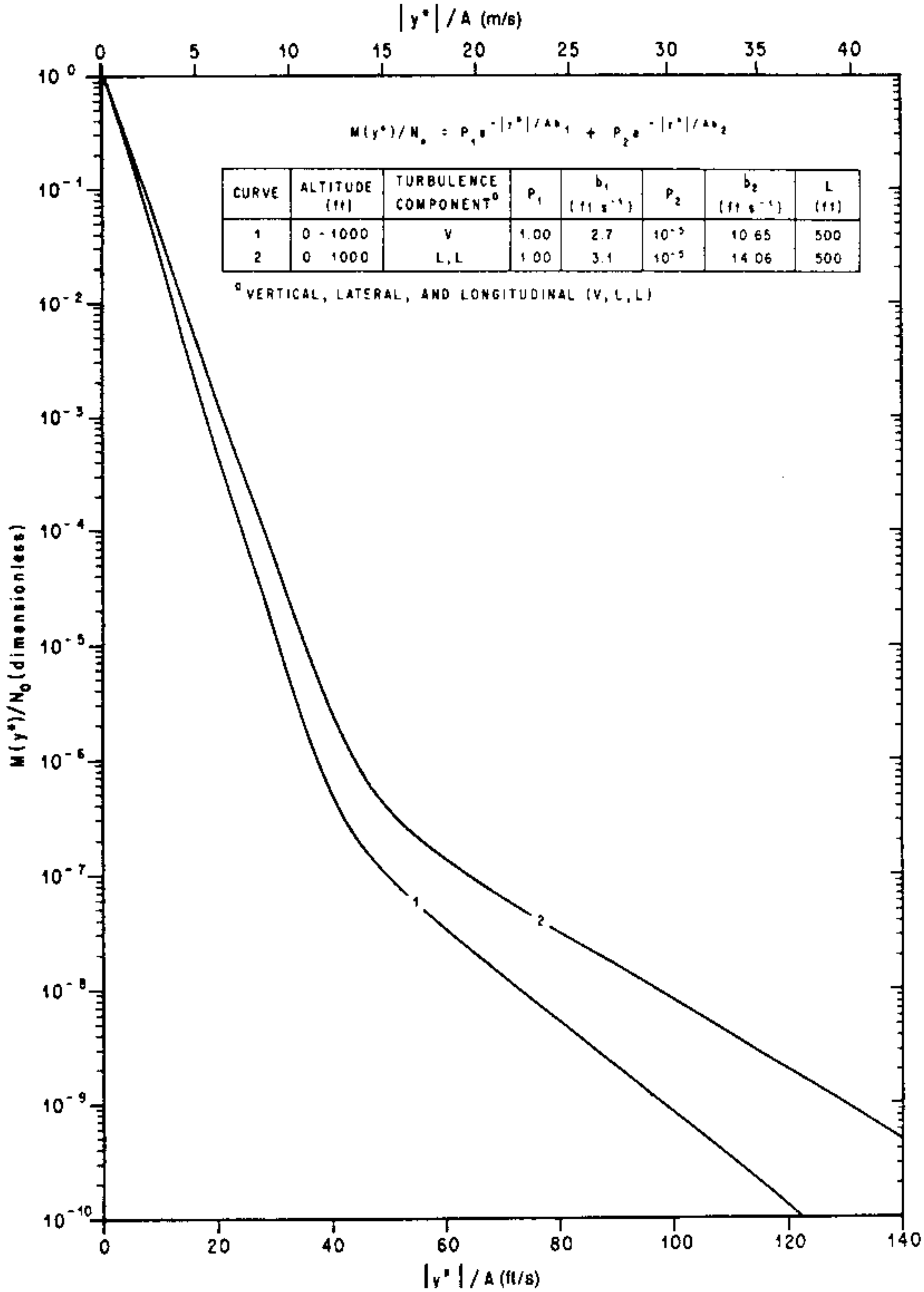
In this equation, $F_y$ is the spectrum of $y$ and

$$s_y = \left[\int_0^\infty F_y(W)\, dW\right]^{\frac{1}{2}}\ . \tag{2.87}$$

The standard deviation of $s_y$ is related to standard deviation of turbulence through equation (2.84) and $\sigma$ is distributed according to equation (2.82). Accordingly, the number of fluctuations of $y$ that exceed $y^*$ for standard deviations of turbulence in the interval $s$ to $s+ds$ is $N(y^*)p(s)ds$, so that integration over the domain $0 < s < \infty$ yields

$$\frac{M(y^*)}{N_0} = P_1 \exp\left(-\frac{|y^*|}{b_1A}\right) + P_2 \exp\left(-\frac{|y^*|}{b_2A}\right)\ , \tag{2.88}$$

where $M(y^*)$ is the overall expected number of fluctuations of $y$ that exceed $y^*$ with positive slope. To apply this equation, the engineer needs only to calculate $A$ and $N_0$ and specify the risk of failure he wishes to accept. The appropriate values of $P_1$, $P_2$, $b_1$, and $b_2$.are given in Table 2-76. Figures 2-40 and 2-41 give plots of $M(y^*)/N_0$ as a function of $|y^*|/A$ for the various altitudes for the design data given in Table 2-76. Table 2-77 provides a summary of the units of the various quantities in this model.




| CURVE | ALTITUDE (ft) | TURBULENCE COMPONENT[a] | $P_1$ | $b_1$ (ft s$^{-1}$) | $P_2$ | $b_2$ (ft s$^{-1}$) | L (ft) |
|---|---|---|---|---|---|---|---|
| 1 | 0 - 1000 | V | 1.00 | 2.7 | $10^{-5}$ | 10.65 | 500 |
| 2 | 0 - 1000 | L, L | 1.00 | 3.1 | $10^{-5}$ | 14.06 | 500 |

FIGURE 2-40. Exceedance Curves for the Vertical, Lateral, and Longitudinal Components of Turbulence for the 0- To 1,000-Ft Altitude Range.

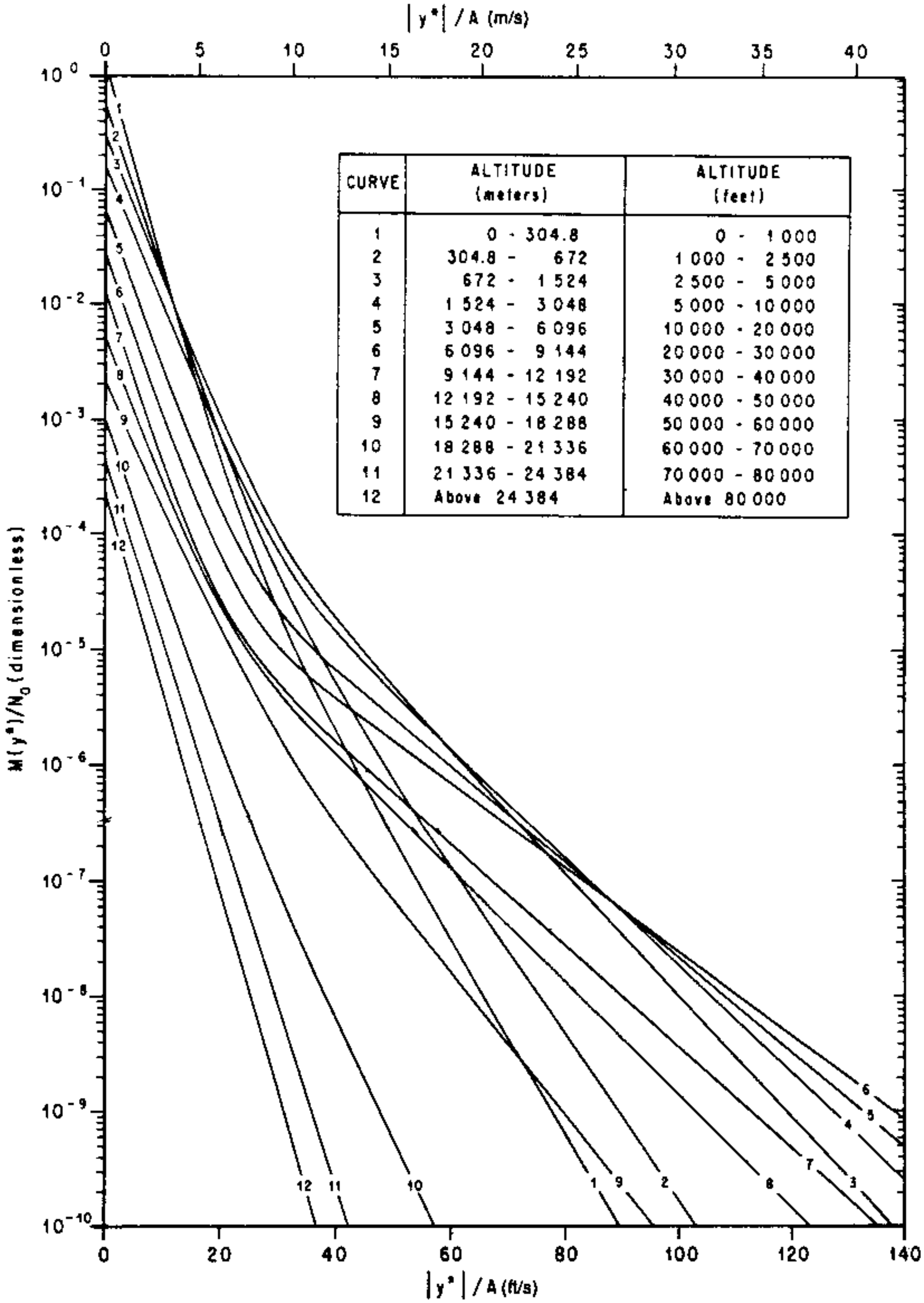



FIGURE 2-41. Exceedance Curves for the Vertical, Lateral, and Longitudinal Components of Turbulence for Various Altitude Ranges.

TABLE 2-77. Metric And U.S. Customary Units of Various Quantities in the Turbulence Model For Horizontally Flying Vehicles.

| Quantity | Metric Units | U.S. Customary Units |
|---|---|---|
| $\Omega$ | rad/m | rad/ft |
| $\Phi_u, \Phi_w$ | $m^2/s^2$/rad/m | $ft^2/s^2$/rad/ft |
| $s^2$ | $m^2/s^2$ | $ft^2/s^2$ |
| $L$ | m | ft |
| $b_1, b_2$ | m/s | ft/s |
| $P_1, P_2$ | dimensionless | dimensionless |
| $s_y/A$ | m/s | ft/s |
| $\|y^*\|/A$ | m/s | ft/s |
| $N_0, N, M$ | rad/s | rad/s |

2.3.13.1 Application of Power Spectral Model. To apply equation (2.88), the engineer can either calculate $A$ and $N_0$ and then calculate the load quantity $y^*$ for a specified value of $M(y^*)$, or calculate $A$ and calculate the load quantity $y^*$ for a specified value of $M(y^*)/N_0$. These design criteria are consistent with the limit load capability of present day commercial aircraft. The criterion in which $M(y^*)$ is specified is suitable for a mission analysis approach to the design problem. The criterion in which $M(y^*)/N_0$ is specified is suitable for a design envelope approach to aircraft design.

In the design envelope approach, it is assumed that the airplane operates 100 percent of the time at its critical design envelope point. The philosophy is that if the vehicle can operate 100 percent of the time at any point on the envelope, it can surely operate adequately in any combination of operating points in the envelope. A new vehicle is designed on a limit load basis for a specified value of $M/N_0$. Accordingly, $M/N_0 = 6 \times 10^{-9}$ is suitable for the design of commercial aircraft. To apply this criterion, all critical altitudes, weights, and weight distributions are specified configurations with equation (2.88) for $M/N_0 = 6 \times 10^{-9}$.

In the mission analysis approach, a new aircraft is designed on a limit load basis for $M = 2 \times 10^{-5}$ load exceedances per hour. To apply this criterion, the engineer must construct an ensemble of flight profiles which define the expected range of payloads and the variation with time of speed, altitude, gross weight, and center of gravity position. These profiles are divided into mission segments, or blocks, for analysis; and average or effective values of the pertinent parameters are defined for each segment. For each mission segment, values of $A$ and $N_0$ are determined by dynamic analysis. A sufficient number of load and stress quantities are included in the dynamic analysis to assure that stress distributions throughout the structure are realistically or conservatively defined. Now the contribution of $M(y^*)$ from the ith flight segment is $t_i M_i(y^*/T)$, where $t_i$ is the amount of time spent in the ith flight regime (mission segment), $T$ is the total time flown by the vehicle over all mission segments, and $M_i(y^*)$ is the exceedance rate associated with the ith segment. The total exceedance rate for all mission segments, $k$, is

$$M(y^*) = \sum_{i=1}^{k} \frac{t_i}{T} N_{0_i} \left( P_1 e^{-\frac{|y^*|}{b_1 A}} + P_2 e^{-\frac{|y^*|}{b_2 A}} \right) , \qquad (2.89)$$

where subscript $i$ denotes the ith mission segment. The limit gust load quantity $|y^*|$ can be calculated with this formula upon setting $M(y^*) = 2 \times 10^{-5}$ exceedances per hour.

The previously mentioned limit load criteria were derived for commercial aircraft which are normally designed for 50,000-h lifetimes. Therefore, to apply these criteria to horizontally flying aerospace vehicles which will have relatively short lifetimes would be too conservative. However, it is possible to modify these criteria so that they will reflect a shorter vehicle lifetime. The probability $F_p$ that a load will be exceeded in a given number of flight hours $T$ is

$$F_p = 1 - e^{-TM} \ . \qquad (2.90)$$

If it is assumed that the limit load criterion $M = 2 \times 10^{-5}$ exceedances per hour is associated with an aircraft with a lifetime $T$ equal to 50,000 h, this means that $F_p = 0.63$; i.e., there is a 63-percent chance that an aircraft design for a 50,000-h operating lifetime will exceed its limit load capability at least once during its operating lifetime. This high failure probability, based on limit loads, is not excessive in view of the fact that an aircraft will receive many inspections on a routine basis during its operating lifetime. In addition, after safety factors are applied to the design limit loads, the ultimate load exceedance rate will be on the order of $10^{-8}$ exceedances per hour. Substitution of this load exceedance rate into equation (2.90) for $T = 50{,}000$ h yields a failure probability, on an ultimate load basis, of $F_p = 0.0005$. This means that there will be only a 0.05-percent chance that an aircraft will exceed its ultimate load capability during its operating lifetime of 50,000 h. Thus, a failure probability of $F_p = 0.63$ in the limit load basis is reasonable for design. Let us now assume that $F_p = 0.63$ is the limit load design failure probability so that equation (2.90) can be used to calculate design values of $M$ associated with a specified vehicle lifetime. Thus, for example, if we expect a vehicle to fly only 100 h, then according to equation (2.90), we have $M = 10^{-2}$ exceedances per hour. Similarly, if we expect a vehicle to be exposed to the atmosphere for 1,000 h of flight, then $M = 10^{-3}$ exceedances per hour.

The corresponding design envelope criterion can be obtained by dividing the preceding calculated values of $M$ by an appropriate value of $N_0$. In the case of the 50,000-h criterion, we have $M/N_0 = 6\times 10^{-9}$ and $M = 2\times 10^{-5}$ exceedances per hour, so that an estimate of $N_0$ for purposes of obtaining a design criterion is $N_0 = 0.333\times 10^4$ h$^{-1}$. Thus, upon solving equation (2.90) for $M$ and dividing by $N_0 = 0.333\times 10^4$ h$^{-1}$, the design envelope criterion takes the form

$$\frac{M}{N_0} = \frac{3\times 10^{-4}}{T} \ , \qquad (2.91)$$

where we have used $F_p = 0.63$. Thus, for a 100-h aircraft, the design envelope criterion is $M/N_0 = 3\times 10^{-6}$ and for a 1,000-h aircraft $M/N_0 = 3\times 10^{-7}$.

It is recommended that the power spectral approach be used in place of the standard discrete gust methods. Reasonably discrete gusts undoubtedly occur in the atmosphere; however, there is accumulating evidence that the preponderance of gusts are better described in terms of continuous turbulence models. It has been accepted that clear air turbulence at moderate intensity levels is generally continuous in nature. Thunderstorm gust velocity profiles are now available in considerable quantity, and they almost invariably display the characteristics of continuous turbulence. Also, low-level turbulence is best described with power spectral methods. A power spectral method of load analysis is not necessarily more difficult to apply than a discrete gust method. The present static load “plunge-only discrete gust methods” can, in fact, be converted to a power spectral basis by making a few simple modifications in the definitions of gust alleviation factor and the design discrete gust. To be sure, this simple rigid-airplane analysis does not exploit the full potentiality of the power spectral approach, but it does account more realistically for the actual mix of gust gradient distances in the atmosphere and the variation of gust intensity with gradient distance.

2.3.14 Turbulence Model for Flight Simulation*. The lateral and vertical components of turbulence are perpendicular to the relative mean wind vector and act in the lateral and vertical directions relative to the vehicle flight path. For simulation of turbulence in either an analog or digital fashion, the turbulence realizations are to be generated by passing a white noise process through a passive filter. The model of turbulence as given in section 2.3.13 is not particularly suited for the simulation of turbulence with white noise because the von Karman spectra given by equations (2.76) and (2.79) are irrational. Thus, for engineering purposes, the Dryden spectra may be used for simulation of continuous random turbulence. They are given by

$$\text{Longitudinal: } F_u(W) = s^2 \frac{2L}{p} \frac{1}{1+(LW)^2} \,, \qquad (2.92)$$

$$\text{Lateral and Vertical: } F_w(W) = s^2 \frac{L}{p} \frac{1+3(LW)^2}{\left[1+(LW)^2\right]^2} \,. \qquad (2.93)$$

Since these spectra are rational, a passive filter may be generated. It should be noted that the Dryden spectra are somewhat similar to the von Karman spectra. As $WL \rightarrow 0$, the Dryden spectra asymptotically approach the von Karman spectra. As $WL \rightarrow \infty$ the Dryden spectra behave like $(WL)^{-2}$, while the von Karman spectra behave like $(WL)^{-5/3}$. Thus, the Dryden spectra depart from the von Karman spectra by a factor proportional to $(WL)^{-1/3}$ as $WL \rightarrow \infty$, so that at sufficiently large values of $WL$ the Dryden spectra will fall below the von Karman spectra. However, this deficiency in spectral energy of the Dryden spectra with respect to the von Karman spectra is not serious from an engineering point of view. If the capability to use the von Karman spectra is already available, the user should use it in flight simulation rather than the Dryden spectra.

The spectra as given by equations (2.92) and (2.93) can be transformed from the wave number ($W$) domain to the frequency domain ($w$, rad/s) with a Jacobian transformation by noting that $W = w/V$, so that

$$F_u(w) = \frac{L}{V} \frac{2s^2}{p} \frac{1}{1+\left(\frac{Lw}{v}\right)^2} \,, \qquad (2.94)$$

$$F_w(w) = \frac{L}{V} \frac{s^2}{p} \frac{1+3\left(\frac{Lw}{V}\right)^2}{\left[1+\left(\frac{Lw}{V}\right)^2\right]^2} \,. \qquad (2.95)$$

The quantity $V$ is the magnitude of the mean wind vector relative to the aerospace vehicle, $u-e$. The quantities $u$ and $e$ denote the velocity vectors of the mean flow of the atmosphere and the aerospace vehicle relative to the Earth. In the region above the 300-m level of the longitudinal component of turbulence is defined to be the component of turbulence parallel to the mean wind vector relative to the aerospace vehicle ($u-e$).

---

*Details on simulations should be requested from Environments Group, Marshall Space Flight Center, AL 35812.

2.3.14.1 Transfer Functions. Atmospheric turbulence can be simulated by passing white noise through filters with the following frequency response functions:

$$\text{Longitudinal: } F_u(jw) = \frac{(2k)^{\frac{1}{2}}}{a+jw}, \tag{2.96}$$

$$\text{Lateral and Vertical: } F_w(j\omega) = \frac{(3k)^{\frac{1}{2}}\left(\frac{a}{\sqrt{3}} + j\omega\right)}{(a + j\,\omega)^2}, \tag{2.97}$$

where

$$a = \frac{V}{L}, \tag{2.98}$$

$$k = \frac{as^2}{p}. \tag{2.99}$$

To generate the three components of turbulence, three distinct uncorrelated Gaussian white noise sources should be used.

To define the rate of change of gust velocities about the pitch, yaw, and roll axes for simulation purposes, a procedure consistent with the preceding formulation can be found in reference 2-41, section 3.7.5, "Application of Turbulence Models and Analyses." This should be checked for applicability.

2.3.14.2 Boundary Layer Turbulence Simulation. The turbulence in the atmospheric boundary layer, defined here for engineering purposes to be approximately the first 300 m of the atmosphere, is inherently anisotropic. To simulate this turbulence as realistically as possible, the differences between the various scales and intensities of turbulence should be taken into account. There are various problems associated with developing an engineering model of turbulence for simulation purposes. The most outstanding one concerns how one should combine the landing or takeoff steady-state wind and turbulence conditions near the ground (18.3-m level, for example) with the steady-state wind and turbulence conditions at approximately the 300-m level. The wind conditions near the ground are controlled by local conditions and are usually derived from considerations of the risks associated with exceeding the design takeoff or landing wind condition during any particular mission. The turbulence environments at and above the 300-m level are controlled by relatively large-scale conditions rather than local landing or takeoff wind conditions, and these turbulence environments are usually derived from considerations of the risks associated with exceeding the design turbulence environment during the total life or total exposure time of the vehicle to the natural environment. The use of the risk associated with exceeding the design turbulence environment during the total life of the vehicle is justified on the basis that, if the landing conditions are not acceptable, the pilot has the option to land at an alternate airfield and thus avoid the adverse landing wind conditions at the primary landing site. Similarly, in the takeoff problem, the pilot can wait until the adverse low-level wind and turbulence conditions have subsided before taking off. The use of the risk associated with exceeding the design turbulence environment during the total life of the vehicle above the atmospheric boundary layer to develop design turbulence environments for vehicle design studies is justified because the pilot does not have the option of avoiding adverse flight turbulence conditions directly ahead of the vehicle. In addition, the art of forecasting in-flight turbulence has not progressed to the point where a flight plan can be established which avoids in-flight turbulence with a reasonably small risk so that design environments can be established on a per flight basis rather than on a total lifetime basis.

How does one then establish a set of values for $L$ and $s$ for each component of turbulence which merges together these two distinctly different philosophies? It is recommended that design values for each component of turbulence be established at the 18.3-m and 304.8-m levels based on the previously stated philosophies. Once these values of $s$ and $L$ are established, the corresponding values between 18.3-m and 304.8-m levels can be obtained with the following interpolation formulas

$$s\,(H) = s_{18.3}\left(\frac{H}{18.3}\right)^{p} \,, \tag{2.100}$$

$$L(H) = L_{18.3}\left(\frac{H}{18.3}\right)^{q} \,, \tag{2.101}$$

where $s(H)$ and $L(H)$ are the values of $s$ and $L$ at height $H$ above natural grade, $s_{18.3}$ and $L_{18.3}$ are the values of $s$ and $L$ at the 18.3-m level, and $p$ and $q$ are constants selected such that the appropriate values of $s$ and $L$ occur at the 304.8-m level. Representative values of $L_{18.3}$ for the Dryden spectrum are given by

$$L_{u_{18.3}} = 31.5\,m \;;\; L_{v_{18.3}} = 18.4\,m \,;\; L_{w_{18.3}} = 10.0\,m \,, \tag{2.102}$$

where subscripts $u$, $v$, and $w$ denote the longitudinal, lateral, and vertical components of turbulence. The corresponding design values of $s_{18.3}$ are given by

$$s_{u_{18.3}} = 2.5 u_{*_o} \,, \tag{2.103}$$

$$s_{v_{18.3}} = 1.91 u_{*_o} \,, \tag{2.104}$$

$$s_{w_{18.3}} = 1.41 u_{*_o} \,, \tag{2.105}$$

where $u_{*0}$ is the surface friction velocity which is given by

$$u_{*_0} = 0.4\frac{\overline{u}_{18.3}}{ln\left(\frac{18.3}{z_0}\right)} \,. \tag{2.106}$$

The quantity $\overline{u}_{18.3}$ is the mean wind or steady-state wind at the 18.3-m level, $z_0$ is the surface roughness length (section 2.2.6.2), and SI units are understood. The quantity $\overline{u}_{18.3}$ is related to the 18.3-m level peak wind speed $u_{18.3}$ (section 2.2.4) through the equation

$$\overline{u}_{18.3} = \frac{u_{18.3}}{G_{18.3}} \,, \tag{2.107}$$

where $G_{18.3}$ is the 18.3-m level gust factor (section 2.2.7.1) associated with a 1-h average wind. This gust factor is a function of the 18.3-m level peak wind speed so that, upon specifying $u_{18.3}$ and the surface roughness length, the quantity $u_{*0}$ is defined by equation (2.106).

The values of $L$ and $s$ must satisfy the Dryden isotropy conditions demanded by the equation of mass continuity for incompressible flow. These isotropy conditions are given by

$$\frac{s_u^2}{L_u} = \frac{s_v^2}{L_v} = \frac{s_w^2}{L_w} \;, \tag{2.108}$$

and must be satisfied at all altitudes. The length scales given by equation (2.102) and the standard deviations of turbulence given by equations (2.103) through (2.105) were selected so that they satisfy the isotropy condition given by equation (2.108); i.e.,

$$\frac{s_{u_{18.3}}^2}{L_{u_{18.3}}} = \frac{s_{v_{18.3}}^2}{L_{v_{18.3}}} = \frac{s_{w_{18.3}}^2}{L_{w_{18.3}}} \;. \tag{2.109}$$

At the 304.8-m level, equation (2.108) is automatically satisfied because $s_u = s_v = s_w$ and $L_u = L_v = L_w$.

To calculate the value of $s_{304.8}$ appropriate for performing a simulation, the following procedure is used to calculate the design instantaneous gust from which the design value of $s_{304.8}$ shall be obtained. The procedure consists of specifying the vehicle lifetime $T$; calculating the limit load design value of $M/N_0$ with equation (2.76) to (2.80); and then calculating the limit load instantaneous gust velocity, $w^*$, say, with equation (2.88) for $A = 1$ with the values of $P_1$, $P_2$, $b_1$, and $b_2$ associated with the 0–304.8-m height interval for climb, cruise, and descent in Table 2-76. The instantaneous gust velocity $w^*$ should be associated with the 99.98-percent value of gust velocity for a given realization of turbulence. In addition, the turbulence shall be assumed to be Gaussian, so that the value of $s_{304.8}$ and the values of $s$ at the 18.3-m level (equations (2.103) through (2.105)) shall be used to determine the values of $p$ for each component of turbulence with equation (2.100); i.e.,

$$p = 0.356 \, ln\left(\frac{s_{304.8}}{s_{18.3}}\right) \;. \tag{2.110}$$

The integral scale of turbulence at the 304.8-m level appropriate for simulation of turbulence with the Dryden turbulence model is $L_{304.8} = 190$ m. This scale of turbulence and the 18.3-m level scales of turbulence given by equation (2.102) yield the following values of $q$ appropriate for the simulation of turbulence with the Dryden turbulence model in the atmospheric boundary layer:

$$q_u = 0.64 \;\; ; \;\; q_v = 0.83 \;\; ; \;\; q_w = 1.05 \;\; . \tag{2.111}$$

The vertical distributions of $s$ and $L$ given by equations (2.100) and (2.101) satisfy the isotropy condition given by equation (2.108).

Below the 18.3-m level, $s$ and $L$ shall take on constant values equal to corresponding 18.3-m level values.

The steady-state wind profile to be used with this model shall be obtained by the procedure given in section 2.3.9.3 for merging ground wind and in-flight wind profile envelopes.

To determine the steady-state wind direction, $q(z)$ at any level $H$ between the surface and the 1,000-m level, use the following formula

$$q\,(H) = q_{1,000} + \left[ 2\left(\frac{H-1{,}000}{1{,}000}\right) + \left(\frac{H-1{,}000}{1{,}000}\right)^2 \right] \Delta \;,$$

where $q_{1,000}$ is the selected 1,000-m level wind direction and $H$ is altitude above the surface of the Earth in meters. The quantity $\Delta$ is the angle between the wind vectors at the 10-, and 1,000-m levels.

This quantity for engineering purposes is distributed according to a Gaussian distribution with mean value and standard deviation given by

$$\overline{\Delta} = 31° \ , \ \overline{u}_{1,000} \leq 4 \, \mathrm{m\,s^{-1}} \ ,$$

$$\overline{\Delta} = 31 - 2.183 \, ln\left(\frac{\overline{u}_{1,000}}{4}\right) \ , \ \overline{u}_{1,000} > 4 \, \mathrm{m\,s^{-1}} \ ,$$

$$s_{\Delta} = 64° \ , \ \overline{u}_{1,000} \leq 4 \, \mathrm{m\,s^{-1}} \ ,$$

$$s_{\Delta} = 63 \, e^{-0.0531 \, (\overline{u}_{1,000} - 4)} \ , \ \overline{u}_{1,000} > 4 \, \mathrm{m\,s^{-1}} \ ,$$

where $\overline{u}_{1,000}$ is the 1,000-m level steady-state wind speed. To avoid unrealistic wind direction changes, $\Delta$, between the surface and the 1,000-m level, only those values of $\Delta$ that occur in the interval $-180° \leq 0 \leq 180°$ should be used. It is recommended that ±1-percent risk wind direction changes be used for vehicle design studies.

To apply this model, the longitudinal component of turbulence shall be assigned to be that component of turbulence parallel to the horizontal component of the relative wind vector. The lateral component of turbulence is perpendicular to the longitudinal component and lies in the horizontal plane. The vertical component of turbulence is orthogonal to the horizontal plane.

The following procedure shall be used to calculate profiles of $s$ and $L$ in the first 304.8 m of the atmosphere for simulation of turbulence with the Dryden turbulence model:

a. Specify the peak wind speed at the 18.3-m level consistent with the accepted risk of exceeding the design 18.3-m level peak wind speed.

b. Calculate the steady-state wind speed at the 18.3-m level with equation (2.107).

c. Calculate the surface friction velocity with equation (2.106).

d. Calculate the 18.3-m level standard deviations of turbulence with equations (2.103) through (2.105).

e. Calculate the 304.8-m level standard deviation of turbulence consistent with the accepted risks of encountering the design instantaneous gust during the total exposure of the vehicle to the natural environments (remembering $s_u = s_v = s_w$ at the 304.8-m level).

f. Calculate $p_u$, $p_v$, and $p_w$ with equation (2.110).

g. Calculate the distribution of $s$ and $L$ with equations (2.110) and (2.111) for the altitudes at and between the 18.3- and 304.8-m levels.

h. Below the 18.3-m level, $s$ and $L$ shall take on constant values equal to the 18.3-m level values of $s$ and $L$.

The reader should consult reference 2-42 for a detailed discussion concerning the philosophy and problem associated with the simulation of turbulence for engineering purposes.

2.3.14.3 Turbulence Simulation in the Free Atmosphere (Above 304.8 m). To simulate turbulence in the free atmosphere (above 304.8 m), it is recommended that equations (2.88) and (2.91) and the supporting data in Table 2-76 be used to specify the appropriate values of $s$. The turbulence at these altitudes can be considered to be isotropic for engineering purposes so that the integral scales and intensities of turbulence are independent of direction. Past studies have shown that when the Dryden turbulence model is being used, the scales of turbulence $L$ = 533.4 m in the 304.8- to 672-m altitude band and $L$ = 762 m above the 672-m level in Table 2-76 should be replaced with the values $L$ = 300 m and $L$ = 533 m, respectively (Ref. 2-41). This reduction in scales tends to bring the Dryden spectra in line with the von Karman spectra over the band of wave numbers of the turbulence which are of primary importance in the design of aerospace vehicles. Accordingly, it is recommended that these reduced scales be used in the simulation of turbulence above the 304.8-m level when the Dryden model is being used.

To calculate the values of $s$ above the 304.8-m level appropriate for performing a simulation of turbulence, it is recommended that the procedure used to calculate the 304.8-m level of $s$ be used. The appropriate values of $P_1$, $P_2$, $b_1$, and $b_2$ for the various altitude bands above the 304.8-m level are given in Table 2-76.

Section 2.3.14.5.1 and Table 2-79b give recently updated values of sigma, scale-length, and probability for light, moderate, and severe turbulence, from 1 to 200 km altitude (Ref. 2-60).

2.3.14.4 Design Floor on Gust Environments. If the design lifetime, $T$, is sufficiently small, it is possible that the turbulence models described herein for horizontally and nearly horizontally flying vehicles will result in a vehicle design gust environment which is characterized by discrete gusts with amplitudes less than 9 m s$^{-1}$ for $dm/L$ > 10 in figure 2-42 above the 1-km level. This is especially true for altitudes above the 18-km level. In view of the widespread acceptance of the 9 m s$^{-1}$ gust as a minimum gust amplitude for design studies in the aerospace community and in view of the increased uncertainty in gust data as altitude increases, it is recommended that a floor be established on gust environments for altitudes above the 1-km level so that the least permissible values of $s$ shall be 3.4 m s$^{-1}$. Applications concerning figure 2-42 are described in subsection 2.3.15.

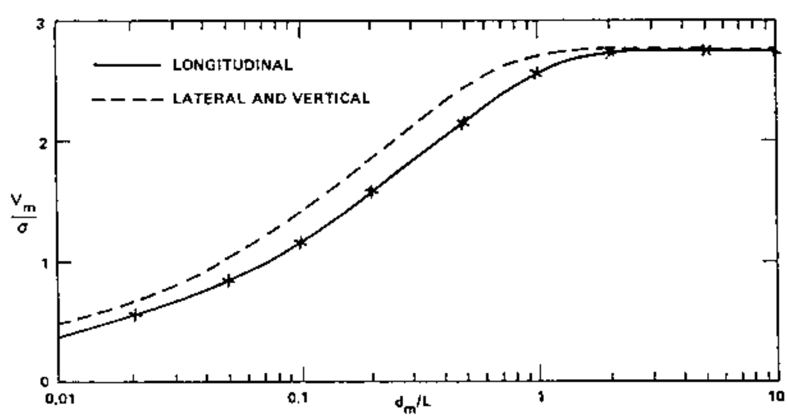



FIGURE 2-42. Nondimensional Discrete Gust Magnitude, $V_m/s$, as a Function Of Nondimensional Gust Half-Width.

2.3.14.5 Multimission Turbulence Simulation. The effects of atmospheric turbulence in both horizontal and near-horizontal flight, during reentry, or atmospheric flight of aerospace vehicles, are important for determining design, control, and "pilot-in-the-loop" effects. A nonrecursive model (based on realistic von Karman spectra) is described. Aerospace vehicles will respond not only to turbulent gusts, but also to spatial gradients of instantaneous gusts (roll, pitch, and yaw). The model described (Ref. 2-43) simulates the vertical and horizontal instantaneous gusts, and three of the nine instantaneous gust gradients, as shown in Table 2-78.

Simulation of turbulence is achieved by passing a white noise process through a filter whose transfer function yields a von Karman power spectrum. The von Karman spectral functions are:

$$F_{ii} = \frac{55 s^2}{36 a p^2} \frac{\left[(aLK)^2 - (aLK_i)^2\right]}{\left[1 + (aLK)^2\right]^{\frac{17}{6}}} , \qquad (2.112)$$

$$F_{\frac{ii}{jj}} = \frac{55 s^2}{36 p^2 a^3 L^2} \frac{(aLK_j)^2 \left[(aLK)^2 - (aLK_i)^2\right]}{\left[1 + (aLK)^2\right]^{\frac{17}{6}}} , \qquad (2.113)$$

TABLE 2-78. Simulated Quantities.

| Variable | Spectrum | Comments |
|---|---|---|
| $U_1$ | $F_{11}$ | Longitudinal gust |
| $U_2$ | $F_{22}$ | Lateral gust |
| $U_3$ | $F_{33}$ | Vertical gust |
| $\partial U_2/\partial X_1$ | $F_{22/33}$ | Yaw* |
| $\partial U_3/\partial X_1$ | $F_{33/11}$ | Pitch |
| $\partial U_3/\partial X_2$ | $F_{33/22}$ | Roll |

*$X_1$, $X_2$, $X_3$ are aircraft fixed coordinates with $X_1$ along the flight path, $X_2$ the lateral direction and $X_3$ vertically upward.

where

$a$ = von Karman constant (1.339)

$s^2$ = variance of turbulence

$k$ = magnitude of wave number vector

$k_i$ = ith component of wave number

$L$ = length scale of turbulence

$F_{ii}$= three-dimensional gust spectrum

$F_{ii/jj}$ = three-dimensional gust gradient spectrum.

Simulating turbulence with a von Karman spectrum is not a simple process, and generating von Karman turbulence fast enough for real-time simulations is difficult. One procedure for real-time simulations involves generating a large number of data sets for each new mission profile. An alternate approach was suggested by Fichtl (Ref. 2-44). In this approach, the turbulent spectra are represented in nondimensional form using the length scale of turbulence, the standard deviation of turbulence, and vehicle true air speed. One set of nondimensional turbulence is generated based on the von Karman spectrum. These data bases can be Fourier analyzed to assure the spectra conform to von Karman's model. To run any mission profile, an efficient real-time routine reads the tapes and transforms them to dimensional format giving the desired output.

The conversion to dimensional values is accomplished as follows:

$$u_i^* = \sigma_i \, U_i \ , \tag{2.114}$$

where

$u_i^*$ = dimensional gust

$\sigma_i$ = standard deviation of ith gust component

$$\frac{\partial u_i^*}{\partial x_j^*} = \frac{\sigma_i}{L_j} \frac{\partial u_i}{\partial x_j} \ , \tag{2.115}$$

where

$\dfrac{\partial u_i^*}{\partial x_j^*}$ = dimensional gust gradient

$L_j$ = jth length scale of turbulence

$$\Delta t^* = \frac{aL_1 T}{V} \ , \tag{2.116}$$

where

$\Delta t^*$ = dimensional time step

$T$ = dimensionless time step.

Note that $\Delta t^*$ is not a constant because $L_1$ and $V$ vary with altitude. To obtain dimensional time, $t_N^*$, a summation process is involved,

$$t_N^* = \sum_{n=0}^{N} \Delta t_N^* = aT \sum_{n=0}^{N} \frac{L_{in}}{V_n} \ . \tag{2.117}$$

For digital simulations, turbulence generated with uneven time steps is undesirable. A simple interpolation routine is used to obtain values of turbulence at equal time steps. Specific values of $\sigma_i$ must be determined for specific applications. Sections 2.3.14.2 through 2.3.14.4 prescribe the techniques for specifying the standard deviation. Values of the turbulent length scales and standard deviations are given in Table 2-79*a* up to 1-km altitudes. Table 2-79*b* specifies light, moderate, and severe turbulence sigmas, length scales, and probabilities versus altitude, from 1 to 200 km. The following paragraph discusses these newer, updated values.

2.3.14.5.1 New Turbulence Statistics/Model. At altitude levels greater than 1,000 m, new turbulence velocity component magnitudes ($\sigma_u$ and $\sigma_w$), and scale lengths ($L_x$ and $L_z$), and their associated probabilities for light, moderate, and severe turbulence have been assembled and modeled (Ref. 2-60). These results are presented in Table 2-79b. This turbulence modeling update was done in order to provide the space shuttle reentry engineering simulation area with a more realistic/less conservative turbulence model when involved with control system fuel expenditures upon reentry/landing.

2.3.15 Discrete Gust Model—Horizontally Flying Vehicles. Often it is useful for the engineer to use discrete gusts in load and flight control system calculations of horizontally flying vehicles. The discrete gust is defined as follows:

$$V_d = 0 \ , \ x < 0$$

$$V_d = \frac{V_m}{2}\left(1 - \cos\frac{\pi x}{d_m}\right) \ , \ 0 \le x \le 2d_m$$

$$V_d = 0 \ , x > 2d_m$$

where $x$ is distance and $V_m$ is maximum velocity of the gust which occurs at position $x = d_m$ in the gust.

To apply the model, the engineer specifies several values of the gust half-width, $d_m$, so as to cover the range of frequencies of the system to be analyzed. To calculate the gust parameter, $V_m$, one enters figure 2-42 with $d_m/L$ and reads out $V_m/\sigma$. Figure 2-42 is based on the Dryden spectrum of turbulence. Accordingly, the procedures outlined in sections 2.3.14.2 and 2.3.14.3 can be used for the specification of the $\sigma$'s and $L$'s to determine the gust magnitude $V_m$ from figure 2-42. In the boundary layer, three values of $V_m$ will occur at each altitude, one for each component of turbulence. In the free atmosphere, the lateral and vertical values of $V_m$ are equal at each altitude. In general, both the continuous random gust model (section 2.3.13 and 2.3.14) and the discrete gust models are often used to calculate vehicle responses, with the procedure producing the larger response being used for design.

2.3.16 Flight Regimes for Use of Horizontal and Vertical Turbulence Models (Spectra and Discrete Gusts). Sections 2.3.8, 2.3.13, and 2.3.15 contain turbulence (spectra and discrete gusts) models for response calculations of vertically ascending and horizontally flying aerospace vehicles.

The turbulence model for the horizontally flying vehicles was derived from wind profile measurements made with vertically ascending jimsphere balloons and smoke trails. In many instances, aerospace vehicles neither fly in a pure horizontal flight mode nor ascend or descend in a strictly vertical flight path. At this time, there does not appear to be a consistent way of combining the turbulence models for horizontal and vertical flight paths without being unduly complicated or overly conservative. In addition, the unavailability of a sufficiently large data sample of turbulence measurements in three dimensions precludes the development of such a combined model.

Accordingly, in lieu of the availability of a combined turbulence model and for the sake of engineering simplicity, the turbulence model in section 2.3.8 should be applied to ascending and descending aerospace vehicles when the angle between the flight path and the local vertical is less than or equal to 30º Similarly, the turbulence model in sections 2.3.13 and 2.3.15 should be applied to aerospace vehicles when the angle between the flight path and the local horizontal is less than or equal to 30º. In the remaining flight path region between 30º from the local vertical and 30º from the local horizontal, both turbulence models should be independently applied and the most adverse responses used in the design.

TABLE 2-79*a*. Variation of Standard Deviation and Length Scale of Turbulence With Height Within the Boundary Layer.*

| | Standard Deviation of Turbulence (Severe) | | | Integral Scales of Turbulence (All) | | |
|---|---|---|---|---|---|---|
| Height (m) | Longitudinal $s_1$ (m/s) | Lateral $s_2$ (m/s) | Vertical $s_3$ (m/s) | Longitudinal $L_1$ (m) | Lateral $L_2$ (m) | Vertical $L_3$ (m) |
| 10 | 2.31 | 1.67 | 1.15 | 21 | 11 | 5 |
| 20 | 2.58 | 1.98 | 1.46 | 33 | 19 | 11 |
| 30 | 2.75 | 2.20 | 1.71 | 43 | 28 | 17 |
| 40 | 2.88 | 2.36 | 1.89 | 52 | 35 | 23 |
| 50 | 2.98 | 2.49 | 2.05 | 61 | 42 | 29 |
| 60 | 3.07 | 2.61 | 2.19 | 68 | 49 | 35 |
| 70 | 3.15 | 2.71 | 2.32 | 75 | 56 | 41 |
| 80 | 3.22 | 2.81 | 2.43 | 82 | 63 | 47 |
| 90 | 3.28 | 2.89 | 2.54 | 89 | 69 | 53 |
| 100 | 3.33 | 2.97 | 2.64 | 95 | 75 | 59 |
| 200 | 3.72 | 3.53 | 3.38 | 149 | 134 | 123 |
| 304.8 | 3.95/4.37 | 3.95/4.37 | 3.95/4.39 | 196/300 | 190/300 | 192/300 |
| 400 | 4.39 | 4.39 | 4.39 | 300 | 300 | 300 |
| 500 | 4.39 | 4.39 | 4.39 | 300 | 300 | 300 |
| 600 | 4.39 | 4.39 | 4.39 | 300 | 300 | 300 |
| 700 | 4.39 | 4.39 | 4.39 | 300 | 300 | 300 |
| 762 | 4.39/5.70 | 4.39/5.70 | 4.39/5.70 | 300/533 | 300/533 | 300/533 |
| 800 | 5.70 | 5.70 | 5.70 | 533 | 533 | 533 |
| 900 | 5.70 | 5.70 | 5.70 | 533 | 533 | 533 |
| 1000 | 5.70 | 5.70 | 4.67 | 832 | 832 | 624 |

*Double entries for a tabulated height indicate a step change in standard deviation or integral scale at that height.

TABLE 2-79b. Mean Horizontal and Vertical Turbulence (Light, moderate, and severe) magnitudes ($\sigma_h$, $\sigma_w$), Wind scale ($l_h$, $L_w$), and Probability for Encountering Turbulence, versus Altitude (MSI).

| | Light Turbulence | | | Moderate Turbulence | | | Severe Turbulence | | | Turbulence Length Scales | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Altitude (MSL) km | Horizontal $\sigma_h$ m/s | Vertical $\sigma_w$ m/s | Probability of Light Turbulence | Horizontal $\sigma_h$ m/s | Vertical $\sigma_w$ m/s | Probability of Moderate Turbulence | Horizontal $\sigma_h$ m/s | Vertical $\sigma_w$ m/s | Probability of Severe Turbulence | Horizontal $L_h$ km | Vertical $L_w$ km |
| 1 | 0.17 | 0.14 | 0.776 | 1.65 | 1.36 | 0.199 | 5.70 | 4.67 | 0.025 | 0.832 | 0.624 |
| 2 | 0.17 | 0.14 | 0.8910 | 1.65 | 1.43 | 0.0979 | 5.80 | 4.75 | 0.0111 | 0.902 | 0.831 |
| 4 | 0.20 | 0.17 | 0.9199 | 2.04 | 1.68 | 0.0738 | 6.24 | 5.13 | 0.0063 | 1.04 | 0.972 |
| 6 | 0.21 | 0.17 | 0.9294 | 2.13 | 1.69 | 0.0650 | 7.16 | 5.69 | 0.0056 | 1.04 | 1.01 |
| 8 | 0.22 | 0.17 | 0.9247 | 2.15 | 1.69 | 0.0704 | 7.59 | 5.98 | 0.0049 | 1.04 | 0.98 |
| 10 | 0.22 | 0.17 | 0.9280 | 2.23 | 1.73 | 0.0677 | 7.72 | 6.00 | 0.0043 | 1.23 | 1.10 |
| 12 | 0.25 | 0.18 | 0.9464 | 2.47 | 1.79 | 0.0502 | 7.89 | 5.71 | 0.0034 | 1.80 | 1.54 |
| 14 | 0.26 | 0.19 | 0.9605 | 2.62 | 1.91 | 0.0368 | 6.93 | 5.05 | 0.0027 | 2.82 | 2.12 |
| 16 | 0.24 | 0.21 | 0.9639 | 2.44 | 2.10 | 0.0337 | 5.00 | 4.31 | 0.0024 | 3.40 | 2.60 |
| 18 | 0.22 | 0.21 | 0.9703 | 2.21 | 2.07 | 0.0277 | 4.07 | 3.81 | 0.0020 | 5.00 | 3.34 |
| 20 | 0.23 | 0.20 | 0.9804 | 2.26 | 1.99 | 0.0180 | 3.85 | 3.38 | 0.0016 | 8.64 | 4.41 |
| 25 | 0.27 | 0.21 | 0.9839 | 2.71 | 2.09 | 0.0146 | 4.34 | 3.34 | 0.0015 | 12.0 | 6.56 |
| 30 | 0.37 | 0.24 | 0.9797 | 3.73 | 2.39 | 0.0185 | 5.60 | 3.59 | 0.0018 | 28.6 | 8.88 |
| 35 | 0.46 | 0.26 | 0.9726 | 4.59 | 2.58 | 0.0249 | 6.89 | 3.87 | 0.0025 | 35.4 | 8.33 |
| 40 | 0.53 | 0.29 | 0.9650 | 5.26 | 2.87 | 0.0318 | 7.89 | 4.30 | 0.0032 | 42.6 | 6.2 |
| 45 | 0.62 | 0.33 | 0.9575 | 6.22 | 3.25 | 0.0386 | 9.33 | 4.88 | 0.0039 | 50.1 | 5.2 |
| 50 | 0.73 | 0.42 | 0.9500 | 7.27 | 4.21 | 0.0455 | 10.90 | 6.31 | 0.0045 | 57.9 | 5.3 |
| 55 | 0.87 | 0.44 | 0.9250 | 8.70 | 4.40 | 0.0682 | 13.06 | 6.60 | 0.0068 | 66.0 | 6.0 |
| 60 | 1.01 | 0.44 | 0.9000 | 10.1 | 4.42 | 0.0917 | 15.1 | 6.63 | 0.0083 | 74.4 | 6.8 |
| 65 | 1.13 | 0.41 | 0.8250 | 11.3 | 4.05 | 0.1620 | 16.9 | 6.0 | 0.0130 | 83.2 | 7.5 |
| 70 | 1.59 | 0.50 | 0.7500 | 15.9 | 5.04 | 0.2336 | 23.8 | 7.5 | 0.0164 | 92.3 | 8.2 |
| 75 | 1.92 | 0.63 | 0.6750 | 19.2 | 6.3 | 0.3066 | 28.7 | 9.5 | 0.0184 | 102 | 9.0 |
| 80 | 2.26 | 0.83 | 0.6000 | 22.6 | 8.3 | 0.3810 | 33.8 | 12.4 | 0.0190 | 111 | 9.7 |
| 85 | 2.73 | 1.03 | 0.4000 | 27.3 | 10.3 | 0.5769 | 40.9 | 15.4 | 0.0231 | 121 | 10.4 |
| 90 | 3.32 | 1.18 | 0.2000 | 33.2 | 11.8 | 0.7767 | 49.8 | 17.7 | 0.0233 | 132 | 11.2 |
| 100 | 3.56 | 1.14 | 0.0000 | 35.6 | 11.4 | 0.9804 | 53.3 | 17.1 | 0.0196 | 153 | 12.7 |
| 120 | 4.23 | 1.07 | 0.0000 | 42.3 | 10.7 | 0.9901 | 63.4 | 16.0 | 0.0099 | 200 | 15.8 |
| 140 | 4.43 | 1.08 | 0.0000 | 44.3 | 10.8 | 0.9901 | 66.4 | 16.1 | 0.0099 | 232 | 17.6 |
| 160 | 4.82 | 1.17 | 0.0000 | 48.2 | 11.7 | 0.9901 | 72.2 | 17.6 | 0.0099 | 270 | 20.0 |
| 180 | 4.89 | 1.18 | 0.0000 | 48.9 | 11.8 | 0.9901 | 73.3 | 17.8 | 0.0099 | 300 | 22.2 |
| 200 | 4.95 | 1.20 | 0.0000 | 49.5 | 12.0 | 0.9901 | 74.2 | 18.1 | 0.0099 | 300 | 24.3 |

2.4 Mission Analysis, Prelaunch Monitoring, and Flight Evaluation. Wind information is useful in the following three general cases of mission analysis:

a. Mission Planning. Since this activity will normally take place well in advance of the mission, the statistical attributes of the wind are used.

b. Prelaunch Operations. Although wind statistics are useful at the beginning of this period, the emphasis is placed upon forecasting and especially wind monitoring.

c. Postflight Evaluation. The effect of the observed winds on the flight is analyzed.

2.4.1 Mission Planning. From wind climatology, the optimum time (month and time of day) and place to conduct the operation can be identified. Missions with severe wind constraints may have such a low probability of success that the risk is unacceptable. Feasibility studies based upon wind statistics can identify these problem areas and answer questions such as: "Is the mission feasible as planned?" and "If the probable risk of mission delay or failure is unacceptably high, can it be reduced by rescheduling to a lighter wind period?"

The following examples are given to illustrate the use of the many wind statistics available to the mission planner.

If it is necessary to remove the ground wind loads damper from a large launch vehicle for a number of hours and this operation must be scheduled some days in advance, the well-known diurnal ground wind variation should be considered for this problem. If, for example, 10.3 m/s (20 knots) were the critical wind speed, there is a 1-percent risk at 0600 e.s.t, but a 13-percent risk at 1500 e.s.t. in July. Obviously, the midday period in the summer should be avoided for this operation. Since these probability values apply to 1-h exposure periods, it is important to recognize that the wind risk depends not only upon wind speed but also upon exposure time. From figure 2-43, the risk in percentage associated with a 15.4 m/s (30-knot) wind at 10 m in February at KSC can be obtained for various exposure times. The upper curve shows the risk increasing from 1 percent for 1-h exposure starting at 0400 e.s.t. to 9.3 percent for 12-h exposure starting at 0400 e.s.t. In this case, the exposure period extends through the high risk part of the day. The lower curve illustrates the minimum risk associated with each exposure period. The lowest risk, of course, can be realized if the starting times are changed to avoid the windy portion of the day. Although there is no space here for the tabulation, wind risk probabilities by month and starting hour for exposure periods from 1 h to 365 days are available upon request.

When winds aloft are considered for mission planning purposes, again the first step might be to acquire general climatological information on the area of concern. From figure 2-44, it is readily apparent that for KSC most strong winds occur during winter in the 10- to 15-km altitude region (this applies also to nearly all midlatitude locations). It is also true that these strong winds are usually westerly.

Next, the mission analyst might ask if a particular mission is feasible. If, for example, the flight is to take place in January and 10- to 15-km altitude winds $\geq$50 m/s are critical, the probability of favorable winds on any given day in January is 0.496. With such a low probability of success, this mission may not be feasible. But, to continue the example, if it is necessary that continuously favorable winds exist for 3 days (perhaps for a dual launch), the probability of success will decrease to 0.256. Obviously an alternate mission schedule must be planned or else the scheduled space vehicle must be provided additional capability through redesign.

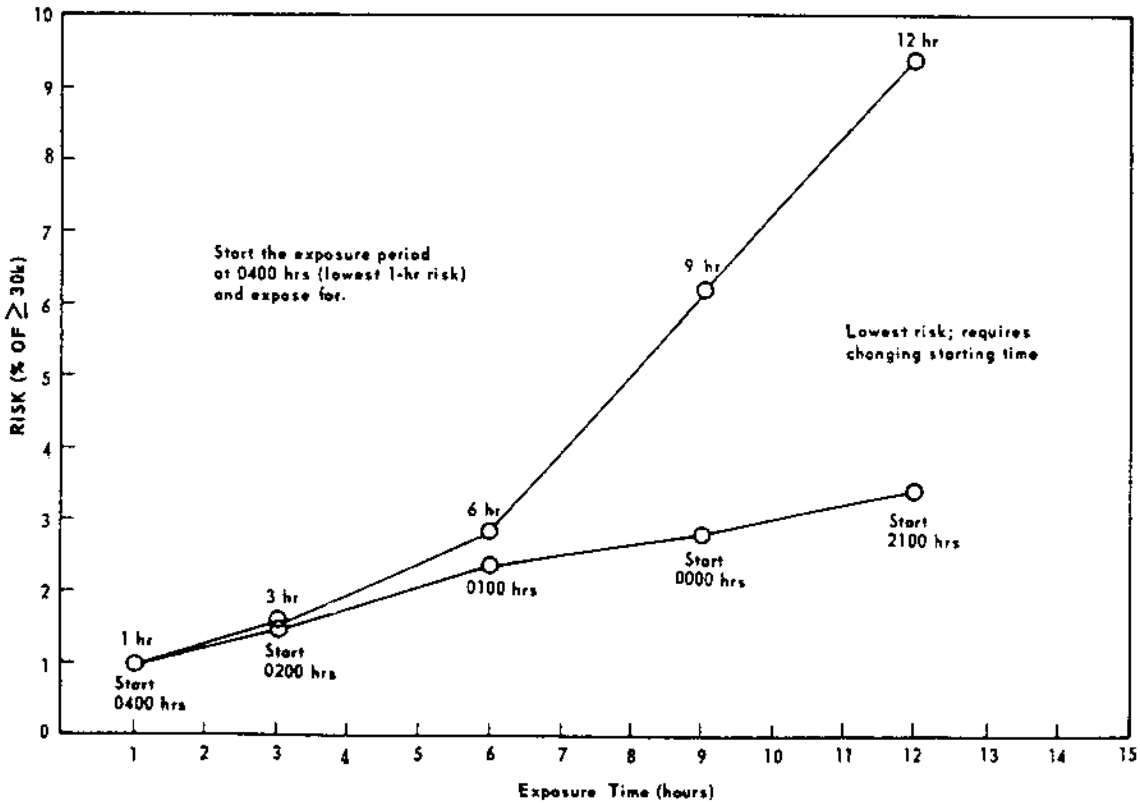



FIGURE 2-43. Example of Wind Risk For Various Exposure Times.

Perhaps the vehicle can remain on the pad in a state of near readiness awaiting launch for several days. In this case, it would be desirable to know that the probability of occurrence of at least one favorable wind speed, for example in a 4-day period, is 0.813. If greater flexibility of operation is desired, one might require four favorable opportunities in 4 days. This probability is 0.550. Now, if consecutive favorable opportunities are required, for example, four consecutive in eight periods, the probability of success will be somewhat lower (0.431).

The mission planner might also gain some useful information from the persistence of the wind aloft within the 10- to 15-km altitude region. The probability of winds <50 m/s on any day in January is 0.496. But if a wind speed <50 m/s does occur, then the probability that the next observed wind 12 h later would be <50 m/s is 0.82, a rather dramatic change. Furthermore, if the wind continues below 50 m/s for five observations, the probability that it will remain there for one more 12-h period is 0.92.

As the time of the operation approaches T-4 to T-1 days, the conditional probability statements assume a more significant role. At this point, as the winds will usually be monitored, the appropriate conditional probability value can be identified and used to greater advantage.

The preceding examples are intended to illustrate the type of analysis that can be accomplished to provide objective data for program decisions. This may best be accomplished by a close working relationship between the analyst and those concerned with the decision.

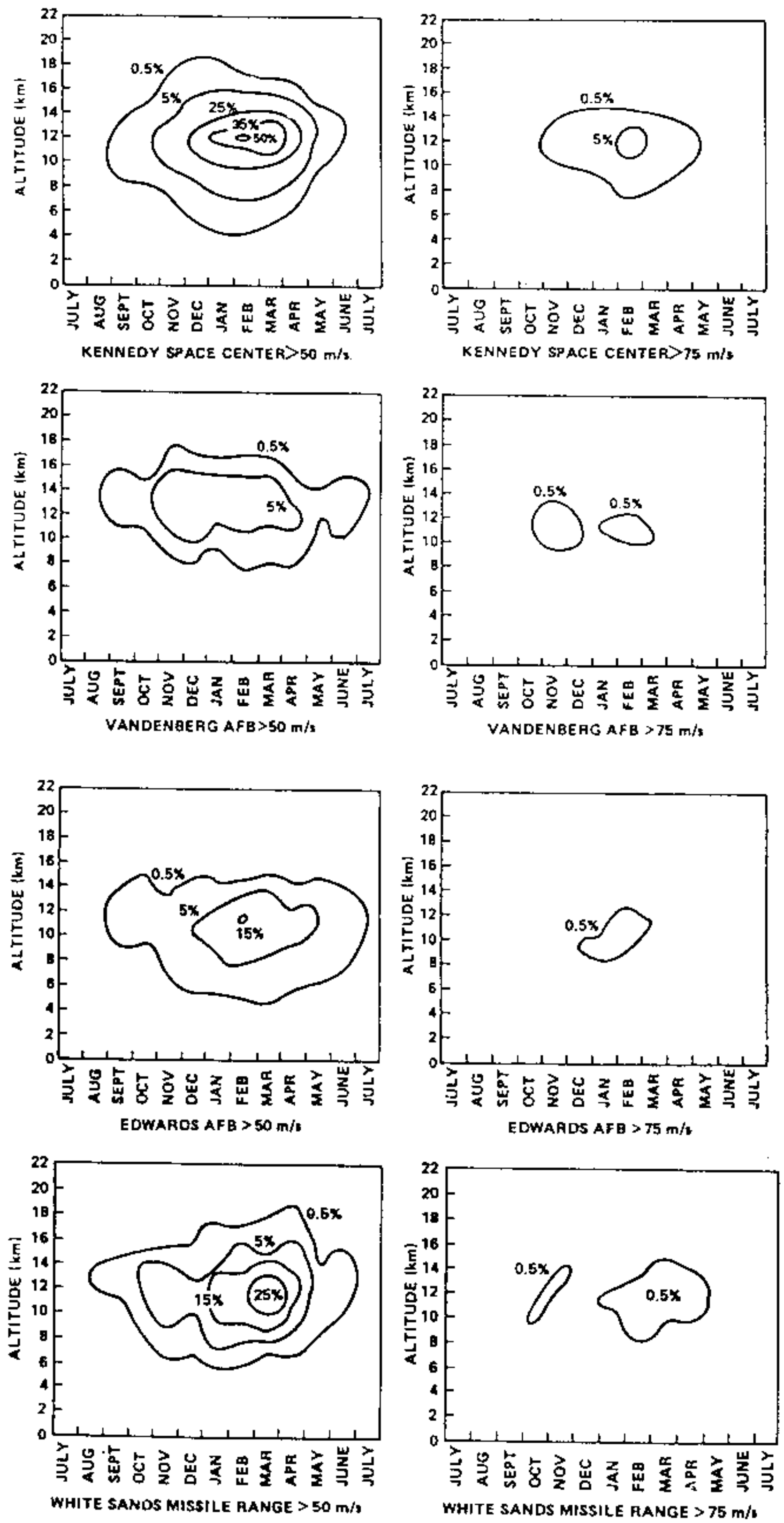



FIGURE 2-44. <u>Frequency of Scalar Wind Speed Exceeding Given Wind Speed as a Function</u>

of Altitude for Stations Indicated.

2.4.2 Prelaunch Wind Monitoring. In-flight winds constitute the major atmospheric parameter in aerospace vehicle and missile design and operations. A frequency content of the wind profile near the bending mode frequencies or wind shear with the characteristics of a step input may exceed the vehicle's structural capabilities (especially on forward stations for the small-scale variations of the wind profile). Wind profiles with high speeds and shears exert high structural loads at all stations on a large space vehicle, and when the influences of bending dynamics are high, even a profile with low speeds and high shears can create large loads (Ref. 2-45).

Because of the possibility of launch into unknown winds, operational missile systems must accept some in-flight loss risk in exchange for a rapid-launch capability. But research and development missiles, and space vehicles in particular, cost so much that the overall success of a flight outweighs the consideration of launch delays caused by excessive in-flight wind loads. If the exact wind profile could be known in advance, it would be a relatively simple task to decide upon the launch date and time. However, there is little hope of accurately forecasting the detailed wind profile far into the future.

Over the years, these situations have increasingly put emphasis on prelaunch monitoring of in-flight winds. Today, prelaunch and profile determination techniques essentially preclude the risk of launching a space vehicle or research and development missile into an in-flight wind condition that would cause it to fail.

The development and operational deployment of the FPS-16 radar/jimsphere system (Ref. 2-46) significantly minimizes vehicle failure risks when properly integrated into a flight simulation program. The jimsphere sensor, when tracked with the FPS-16 or other radar with equal tracking capability, provides a very accurate "all weather" detailed wind profile measurement. FPS-16 radars are available at all national test ranges.

In general, the system provides a wind profile measurement from the surface to an altitude of 17 km in slightly less than 1 h, a vertical spatial frequency resolution of 1 cycle per 200 m, and an rms error of about 0.5 m/s or less for wind velocities averaged over 50-m intervals. The resolution of these data permits calculating the structural loads associated with the first bending mode and generally the second mode of missiles and space vehicles during the critical, high dynamic pressure phase of flight. This provides better than an order-of-magnitude accuracy improvement over the conventional rawinsonde wind profile measurement system.

By employing the appropriate data transmission resources, a detailed wind profile from the FPS-16 radar can be ready for input to the vehicle's flight simulation program within a few minutes after tracking of the jimsphere. The flight simulation program provides flexibility relative to vehicle dynamics and other parameters in order to make maximum use of detailed wind profiles.

If very critical wind conditions exist and the mission requirement dictates a maximum effort to launch with provision for last-minute termination of the operation, then a contingency plan that will provide essentially real-time wind profile and flight simulation data may be employed. This is done while the jimsphere balloon is still in flight.

An example of the FPS-16 radar/jimsphere system data appears in figure 2-45 - the November 8 and 9, 1967, sequence observed during prelaunch activities for the first Apollo/Saturn-V test flight, AS-501. Reference 2-47 contains additional sequential jimsphere wind profile sets for KSC and Point Mugu, CA, respectively. The persistence over a period of 1 h of some small-scale features in the wind profile structure, as well as the rather distinct changes that developed in the profiles over a period of a few hours, is evident.

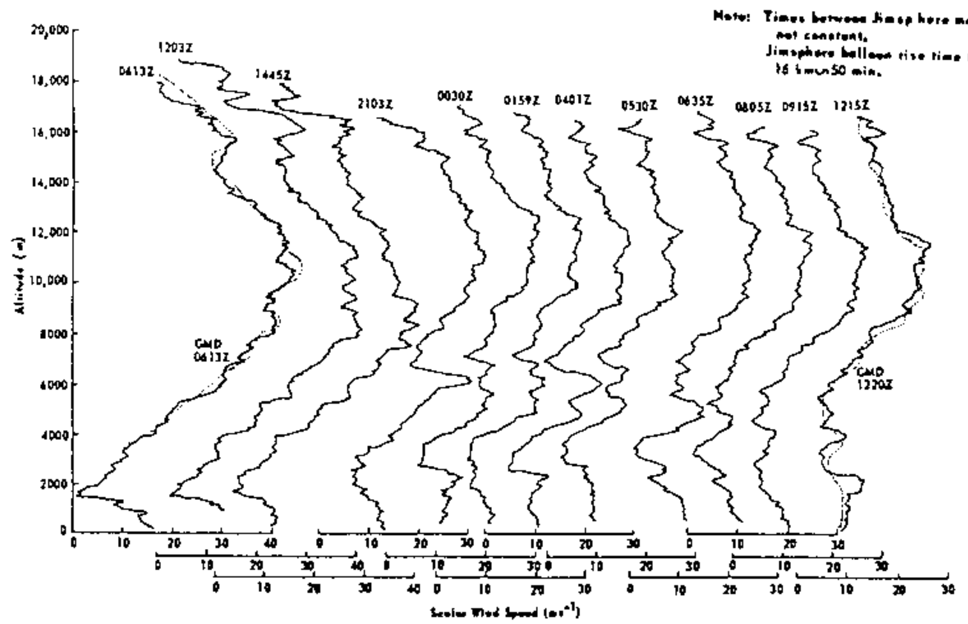


FIGURE 2-45. Examples of the FPS-16 Radar/Jimsphere System Data, November 8-9, 1967.

The FPS-16 radar/jimsphere system (fig. 2-46) was routinely used in the prelaunch monitoring of NASA's Apollo/Saturn and the space shuttle flights. The wind profile data were transmitted to the Johnson Space Center and Marshall Space Flight Center, and the flight simulation results were sent to the launch complex at KSC.

An FPS-16 radar/jimsphere operational measurement program capability exists at all the national test ranges to obtain detailed wind profile data for use in space vehicle and missile response studies, airplane turbulence analysis, atmospheric turbulence investigations, and mesometeorological studies. Sequential measurements similar to those made in support of a Saturn-V launch shown here—of 8 to 10 jimsphere wind profiles approximately 1 h apart—were made on at least 1 day per month for each location. Single profile measurements were also made daily at KSC.

A radar wind profiler is currently operating at KSC and measures wind profiles between 2- and 19-km altitude. The profiler gives better temporal resolution than balloons. Various profiler data bases are available upon request.

### 2.4.3 Post-Flight Evaluation

2.4.3.1 Introduction. Because of the variable effects of the atmosphere upon a large aerospace vehicle at launch and during flight, various meteorological parameters were measured at the time of each vehicle launch, including wind and thermodynamic data at the Earth's surface and up to an altitude of at least 36 km. To make the data available, meteorological tapes were prepared, presentations were made at flight evaluation meetings, memoranda of data tabulations were prepared and distributed, and a summary was written. Reference 2-48 for space shuttle STS-1 is an example of one of the reports with an atmospheric section.

2.4.3.2 Meteorological Data Profiles. Shortly after the launch of each aerospace vehicle under the cognizance of MSFC, a meteorological ascent data profile was prepared by combining the FPS-16 radar/jimsphere wind profile data and the rawinsonde wind profile and thermodynamic data (temperature, pressure, and humidity) observed as near the vehicle launch time as feasible. This was done under the supervision of the MSFC's Earth Science and Applications Division. The meteorological data was normally available within 3 days after launch time and provided data to approximately 36 km. In the meteorological data profile, thermodynamic and wind data above the measured data are given by the Range Reference Atmosphere (Ref. 2-23) and the Global Reference Atmosphere (Ref. 2-49) values. To prevent unnatural jumps in the data when the two types are merged, the data were carefully examined to pick the best altitude for the merging, and a ramping procedure was employed. The meteorological data profiles were made available to all government and contractor groups for their use in the space vehicle launch and flight evaluation. This provides a consistent set of data for all evaluation studies and ensures the best available information of the state of the atmosphere during launch. For space shuttle launches, an SRB descent meteorological data tape was constructed using rawinsonde data taken from a ship stationed near the SRB impact site. Twenty parameters of data were included in the meteorological data tape at 100-ft increments of altitude.* Table 2-80 presents the parametric format of the L–0 atmospheric data profile that is assembled after each NASA-MSFC associated vehicle launch.

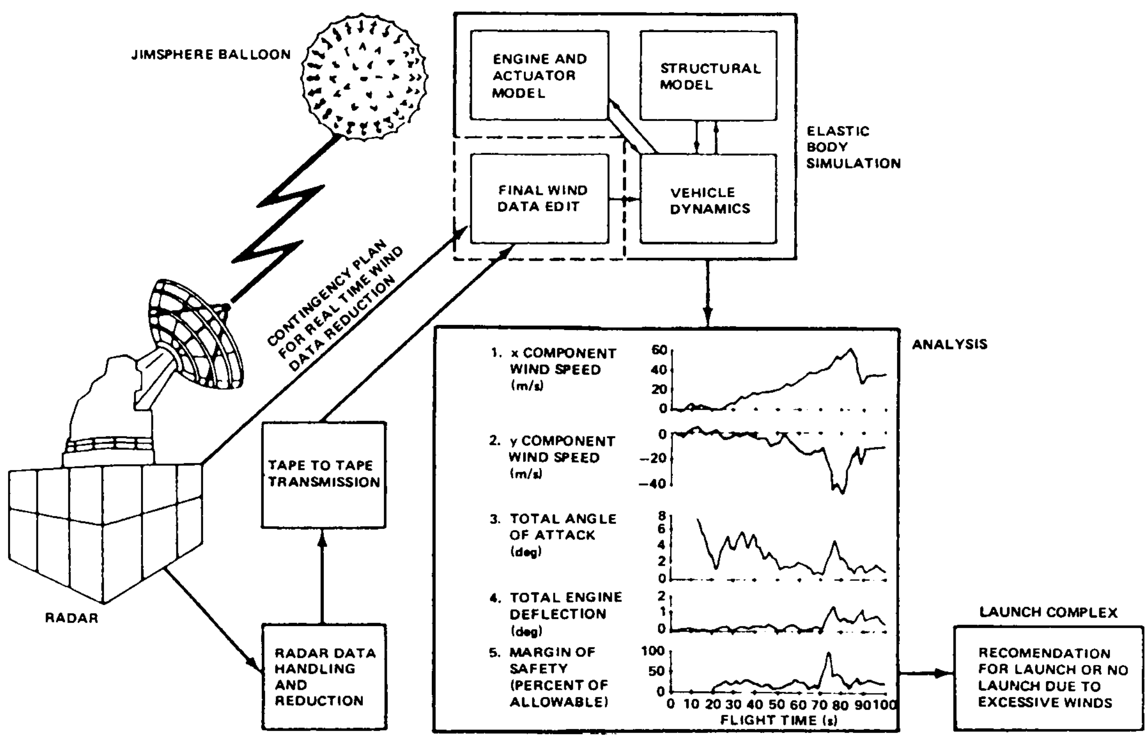



FIGURE 2-46. Operation of the FPS-16 Radar/Jimsphere System.

Pad winds and thermodynamic data were measured and recorded at different heights above the launch pad starting several hours before launch time. Reference 2-50 summarizes atmospheric data observations for 155 flights of NASA/MSFC-related launches. Records and summary reports are maintained on the atmospheric parameters for MSFC-sponsored vehicle test flights conducted at KSC, FL. Requests for summaries of these atmospheric data, or related questions on specific topics, should be directed to the Environments Group, ED44, NASA Marshall Space Flight Center, Alabama 35812.

*Altitude increments of 100 ft were chosen to provide for maximum engineering value and for use of the available atmospheric data and do not necessarily represent the attainable response frequency of the measurements.

TABLE 2-80. Format of Meteorological Data Profile.

| WORD | SYMBOL | DESCRIPTION | UNITS |
|---|---|---|---|
| 1 | LAT | Latitude | degrees, +N |
| 2 | LON | Longitude | degrees, +E to 360 |
| 3 | FLAG | 0 = measured data,<br>1 = modeled data,<br>2 = combined measured and modeled data | |
| 4 | — | Spare | |
| 5 | ALT | Geometric altitude | ft |
| 6 | WS | Horizontal wind speed | ft/s |
| 7 | WD | Directional horizontal wind is coming from relative to true north, North being 0°, increasing positively clockwise | deg |
| 8 | TE | Ambient temperature | °C |
| 9 | PR | Ambient pressure | millibars |
| 10 | D | Ambient density | gram/m$^3$ |
| 11 | DW | Dew point | °C |
| 12 | TEU | Ambient temperature systematic uncertainty | °C |
| 13 | PRU | Ambient pressure systematic uncertainty | millibars |
| 14 | DU | Ambient density systematic uncertainty | gram/m$^3$ |
| 15 | HWSUS | Horizontal wind speed systematic uncertainty | ft/s |
| 16 | HWSUN | Horizontal wind speed noise or fluctuation uncertainty | ft/s |
| 17 | VWSUN | Vertical wind speed noise or fluctuation uncertainty | ft/s |
| 18 | HWDUS | Horizontal wind direction systematic uncertainty | deg |
| 19 | HWDUN | Horizontal wind direction noise or fluctuation uncertainty | deg |
| 20 | | Spare | |

# SECTION 2
# REFERENCES

2-1 Carter, E.A., and Schuknecht, L.A.: “Peak Wind Statistics Associated With Thunderstorms at Cape Kennedy, Florida.” NASA CR-61304, NASA-MSFC, Marshall Space Flight Center, Alabama, August 1969.

2-2 Smith, O.E., Falls, L.W., and Brown, S.C.: “Research Achievements Review.” vol. II, report No. 10, “Terrestrial and Space Environment Research at MSFC,” NASA TM X-53706, NASA-MSFC, Marshall Space Flight Center, Alabama, 1967.

2-3 Lee, R.F., Goodge G.W., and Crutcher, H.L.: “Surface Climatological Information for Twelve Selected Stations for Reentry Vehicles.” NASA CR-61319, Marshall Space Flight Center, Alabama, 1970.

2-4 Goodge, G.W., Bilton, T.H., and Quinlin, F.T.: “Surface Climatological Information for Twelve Selected Stations for Reentry Vehicles.” NASA CR-61342, Marshall Space Flight Center, Alabama, 1971.

2-5 Fichtl, G.H., and McVehil, G.E.: “Longitudinal and Lateral Spectra of Turbulence in the Atmospheric Boundary Layer at the Kennedy Space Center.” Journal of Applied Meteorology, vol. 9, No. 1, February 1970, pp. 51–63.

2-6 Blackadar, A.K., et al.: “Investigation of the Turbulent Wind Field Below 150-M Altitude at the Eastern Test Range.” NASA CR-1410, NASA-MSFC, Marshall Space Flight Center, Alabama, August 1969.

2-7 McVehil, G.E., and Camnitz, H.G.: “Ground Wind Characteristics at Kennedy Space Center.” NASA CR-1418, NASA-MSFC, Marshall Space Flight Center, Alabama, September 1969.

2-8 Fichtl, G.H., Kaufman, J.W., and Vaughn, W.W.: “Characteristics of Atmospheric Turbulence as Related to Wind Loads on Tall Structures.” Journal of Spacecraft and Rockets, vol. 6, No. 12, December 1969, pp. 1396–1403.

2-9 Fichtl, G.H.: “Problems in the Simulation of Atmospheric Boundary Layer Flows.” AGARD-DP-140 (1973) 2-1. (Paper presented at AGARD Flight Mechanics Panel Symposium on “Flight in Turbulence,” England, May 1973.)

2-10 Fichtl, G.H.: “Wind Shear Near the Ground and Aircraft Operations.” Journal of Spacecraft and Rockets, vol. 9, No. 11, November 1972, pp. 765–770.

2-11 Fichtl, G.H.: “Probability Distribution of Vertical Longitudinal Shear Fluctuations.” Journal of Applied Meteorology, vol. 11, No. 6, September 1972, pp. 918–925.

2-12 Fichtl, G.H.: “Standard Deviation of Vertical Two-Point Longitudinal Velocity Differences in the Boundary Layer.” Boundary-Layer Meteorology, vol. 2, 1971, pp. 137–151.

2-13 Luers, J.K., and Reese, J.B.: “Effects of Shear on Aircraft Landing.” NASA CR-2287, NASA-MSFC, Marshall Space Flight Center, Alabama, July 1973.

2-14 Luers, J.K.: "A Model of Wind Shear and Turbulence in the Surface Boundary Layer." NASA CR-2288, NASA-MSFC, Marshall Space Flight Center, Alabama, July 1973.

2-15 Sowa, D.: "Low-Level Wind Shear." D.C. Flight Approach, No. 20, Douglas Aircraft Co., Long Beach, California, 1974.

2-16 Barr, N.M., Gangaas, D.; and Schaeffer, D.R.: "Wind Models for Flight Simulator Certification of Landing and Approach Guidance and Control Systems." Report No. FAA-RD-74-206, U.S. Department of Transportation, Federal Aviation Administration, Washington, DC 20590, December 1974.

2-17 Lewell, W.S., and Williamson, G.G.: "Wind Shear and Turbulence Around Airports." NASA CR-2752, NASA-MSFC, Marshall Space Flight Center, Alabama, October 1976.

2-18 Camp, D.W., and Kaufman, J.W.: "Comparison of Tower Influence on Wind Velocity for NASA's 150-Meter Meteorological Tower and a Wind Tunnel Model of the Tower." Journal of Geophysical Research, vol. 75, No. 6, February 20, 1970.

2-19 Thom, H.C.S.: "New Distributions of Extreme Winds in the United States." Journal of the Structural Division Proceedings of the American Society of Civil Engineers, ST-7, July 1968, pp. 1787–1801.

2-20 Thom, H.C.S.: "Distribution of Extreme Winds Over Oceans." J. Waterways, Harbors, and Coastal Engr. Div., Proc. Am. Soc. Civ. Engr., February 1973, pp. 1–17.

2-21 Falls, L.W., and Brown, S.C.: "Optimum Runway Orientation Relative to Crosswinds." NASA TN D-6930, September 1972.

2-22 Falls, L.W., and Crutcher, H.L.: "Determination of Statistics for Any Rotation of Axes of a Bivariate Normal Elliptical Distribution." NASA TM X-64595, May 1971.

2-23 IRIG Document No. 104-63, Range Reference Atmosphere Documents published by Secretariat, Range Commander's Council, White Sands Missile Range, New Mexico. The following reference atmospheres have been published:

Kwajalein Missile Range, Kwajalein, Marshall Islands, Range Reference Atmosphere, 0- to 70-km Altitude, Document 360-82, December 1982. (AD123424)

Cape Canaveral, Florida, Range Reference Atmosphere, 0- to 70-km Altitude, Document 361-83, February 1983. (ADA125553)

Vandenberg Air Force Base, California, Range Reference Atmosphere, 0- to 70-km Altitude, Document 362-83, April 1983.

Dugway, Utah, Range Reference Atmosphere, 0- to 30-km Altitude, Document 363-83, June 1983.

Wallops Island, Virginia, Range Reference Atmosphere, 0- to 70-km Altitude, Document 364-83, July 1983.

White Sands Missile Range, New Mexico, Range Reference Atmosphere, 0- to 70-km Altitude, Document 365-83, August 1983.

Edwards Air Force Base, California, Range Reference Atmosphere, 0- to 70-km Altitude, Document 366-83, August 1983.

Eglin Air Force Base, Florida, Range Reference Atmosphere, 0- to 30-km Altitude, Document 367-83, September 1983.

Taquac, Guam Island, Range Reference Atmosphere, 0- to 30-km Altitude, Document 368-83, September 1983.

Point Mugu, California, Range Reference Atmosphere, 0- to 70-km Altitude, Document 369-83, September 1983.

Barking Sands, Hawaii, Range Reference Atmosphere, 0- to 70-km Altitude, Document 370-83, December 1983.

Ascension Island, South Atlantic, Range Reference Atmosphere, 0- to 70-km Altitude, Document 371-84, January 1984.

2-24 Falls, L.W.: "Normal Probabilities for Cape Kennedy Wind Components—Monthly Reference Periods for All Flight Azimuths, Altitudes 0 to 70 km." NASA TM X-64771, NASA-MSFC, Marshall Space Flight Center, Alabama, April 16, 1973.

2-25 Falls, L.W.: "Normal Probabilities for Vandenberg AFB Wind Components—Monthly Reference Periods for All Flight Azimuths, 0- to 70-km Altitudes." NASA TM X-64897, NASA-MSFC, Marshall Space Flight Center, Alabama, January 1975.

2-26 Henry. R.M.: "A Statistical Model for Synthetic Wind Profiles for Aerospace Vehicle Design and Launching Criteria." NASA TN D-1813, 1963.

2-27 Bieber, R.E.: "Missile Structural Loads by Nonstationary Statistical Methods." Technical Report No. LMSD 49703, Lockheed Missile and Space Division, Huntsville, Alabama, April 1959. (Also available as DDC AD220595 or NTIS PB157733.)

2-28 Vaughan, W.W.: "Interlevel and Intralevel Correlations of Wind Components for Six Geographical Locations." NASA TN D-561, December 1960.

2-29 Daniels, G.E., and Smith, O.E.: "Scalar and Component Wind Correlations Between Altitude Levels for Cape Kennedy, Florida, and Santa Monica, California." NASA TN D-3815, April 1968.

2-30 Cochrane, J.A., Henry, R.M., and Weaver, W.L.: "Revised Upper Air Wind Data for Wallops Island Based on Serially Complete Data for the Years 1956 to 1964." NASA TN D-4570, NASA-Langley Station, Hampton, Virginia, May 1968.

2-31 Buell, C.E.: "Correlation Functions for Wind and Geographical on Isobaric Surfaces." Journal of Applied Meteorology, vol. II, No. 1, February 1972, pp. 51–59.

2-32 Buell, C.E.: “Variability of Wind With Distance and Time on an Isobaric Surface.” Journal of Applied Meteorology, vol. II, No. 7, October 1972, pp. 1085–1091.

2-33 Truppi, L.E.: “Probabilities of Zero Wind Shear Phenomena Based on Rawinsonde Data Records.” NASA TM X-53452, NASA-MSFC, Marshall Space Flight Center, Alabama, April 27, 1966.

2-34 Camp, D.W., and Susko, M.: “Percentage Levels of Wind Speed Differences Computed by Using Rawinsonde Wind Profile Data From Cape Kennedy, Florida.” NASA TM X-53461, NASA-MSFC, Marshall Space Flight Center, Alabama, May 12, 1966.

2-35 Camp, D.W., and Fox, P.A.: “Percentage Levels of Wind Speed Differences Computed by Using Rawinsonde Wind Profile Data From Santa Monica, California.” NASA TM X-53428, NASA-MSFC, Marshall Space Flight Center, Alabama, October 21, 1966.

2-36 Adelfang, S.I.: “Analysis of Vector Wind Change With Respect to Time for Cape Kennedy, Florida.” NASA CR-15077, NASA-MSFC, Marshall Space Flight Center, Alabama, August 1978.

2-37 Adelfang, S.I.: “Analysis of Vector Wind Change With Respect to Time for Vandenberg Air Force Base, California.” NASA CR-150776, NASA-MSFC, Marshall Space Flight Center, Alabama, August 1978.

2-38 Smith. O.E.: “Vector Wind and Vector Wind Shear Models 0- to 27-km Altitude for Cape Kennedy, Florida, and Vandenberg AFB, California.” NASA-MSFC, Marshall Space Flight Center, Alabama, July 1976.

2-39 Fichtl, G.H.: “Small-Scale Wind Shear Definition for Aerospace Vehicle Design.” Journal of Spacecraft and Rockets, vol. 9, No. 2, February 1972, pp. 79–83.

2-40 Fichtl, G.H., Camp, D.W., and Vaughan, W.W.: “Detailed Wind and Temperature Profiles.” Clear Air Turbulence and It’s Detection, Edited by Yih-Hc Pao and Arnold Goldburg, Plenum Press, New York, 1969, pp. 308–333.

2-41 Chalk, C.R., et al.: “Background Information and User Guide for MIL-F-8758B (ASG), ‘Military Specification—Flying Qualities for Piloted Airplanes.’ ” AFFDL-TR-69-72, Air Force Flight Dynamics Laboratory, Air Force Systems Command, 1969.

2-42 Dutton, J.A.: “Broadening Horizons in Prediction of the Effects of Atmospheric Turbulence on Aeronautical Systems.” AIAA Selected Reprints Series, vol. XIII, The Earth’s Atmosphere, W.W. Vaughan and L.L. DeVries Editors, Published by the American Institute of Aeronautics and Astronautics, New York, 1972.

2-43 Tatom, F.B., and Smith, S.R.: “Advanced Shuttle Simulation Turbulence Tapes (SSTT) User’s Guide.” Engineering Analysis, Incorporated, contract NAS8-33818, September 29, 1981.

2-44 Fichtl, G.H.: “A Technique for Simulating Turbulence for Aerospace Vehicle Flight Simulation Studies.” NASA TM-78141, November 1977.

2-45 Ryan, R.S., Scoggins, J.R., and King, A.W.: “Use of Wind Shears in the Design of Aerospace Vehicles.” Journal of Spacecraft and Rockets, vol. 4, No. 11, November 1967, pp. 1526–1532.

2-46 Vaughan, W.W.: “New Wind Monitoring System Protects R and D Launches.” Journal of Astronautics and Aeronautics, December 1968, pp. 41–43.

2-47 Johnson, D.L., and Vaughan, W.W.: “Sequential High Resolution Wind Profile Measurements.” NASA TP-1354, December 1978.

2-48 Johnson, D.L., Jasper, G., and Brown, S.C.: “Atmospheric Environment for Space Shuttle (STS-1) Launch.” NASA TM-82436, July 1981.

2-49 Justus, C.G., Alyea, F.N., Cunnold, D.M., Jeffries, W.R. III, and Johnson, D.L.: “The NASA/MSFC Global Reference Atmospheric Model—1990 Version (GRAM-90); Part I Technical/Users Manual.” NASA TM-4268, April 1991.

2-50 Johnson, D.L.: “Summary of Atmospheric Data Observations for 155 Flights of MSFC/ABMA Related Aerospace Vehicles.” NASA TM X-64796, NASA-MSFC, Marshall Space Flight Center, Alabama, December 5, 1973.

2-51 Johnson, D.L., and Brown, S.C.: “Surface to 90-km Winds for Kennedy Space Center, Florida, and Vandenberg AFB, California.” NASA TM-78233, July 1979.

2-52 Smith, O.E., Adelfang, S.I., and Brown, R.P.: “Ascent Structural Wind Loads for the National Space Transportation System (NSTS).” Proceedings paper AIAA-88-0293, AIAA 26th Aerospace Sciences Meeting, January 11–14, 1988, Reno, Nevada.

2-53 Smith. O.E., and Austin, L.D., Jr.: “Space Shuttle Response to Ascent Wind Profiles.” AIAA Journal of Guidance Control and Dynamics, vol. 6, No. 5, September–October 1983, pp. 355–360.

2-54 Smith, O.E., and Austin, L.D., Jr.: “Sensitivity Analysis of the Space Shuttle to Ascent Wind Profiles.” NASA TP-1988, March 1982.

2-55 Smith, O.E., Adelfang, S.I., Batts, G.W., and Hill, C.K.: “Wind Models for the NSTS Ascent Trajectory Biasing for Wind Load Alleviation.” NASA TM-100375, August 1989.

2-56 Gumbel, E.J.: “Statistics of Extremes.” Columbia University Press, New York, New York, 1958, 57-10160.

2-57 Gumbel, E.J., Mustafi, C.K., and Smith, O.E.: “Tables of the Probability and Density Functions for the Bivariate Extremal Distributions.” Department of Industrial Engineering, Columbia University, New York, New York, April 1968.

2-58 Gumbel, E.J., and Mustafi, C.K.: “Some Analytical Properties of the Bivariate Extremal Distributions.” American Statistical Association Journal, June 1967, pp. 569–588.

2-59 Smith, S.A.: “Revised Gust Model.” Memo ES44-(147-89), NASA Marshall Space Flight Center, Earth Science and Applications Division, Environmental Analysis Branch, October 24, 1989.

2-60. Justus, C.G., Campbell, C.W., Doubleday, M.K., and Johnson, D.L.: “New Atmospheric Turbulence Model for Shuttle Applications.” NASA TM-4168, January 1990.

2-61 Smith, O. E., and Adelfang, S. I.: “A Compendium of Wind Statistics and Models for the NASA Space Shuttle and other Aerospace Vehicle Programs”. NASA CR-1998-208859, October 1998.